PB80-184765

Waste and Water Management for Conventional Coal Combustion Assessment Report--1979. Volume IV Utilization of FGC Wastes

Arthur D. Little, Inc.
Cambridge, MA

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Mar 80

U.S. Department of Commerce
National Technical Information Service
NTIS

United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

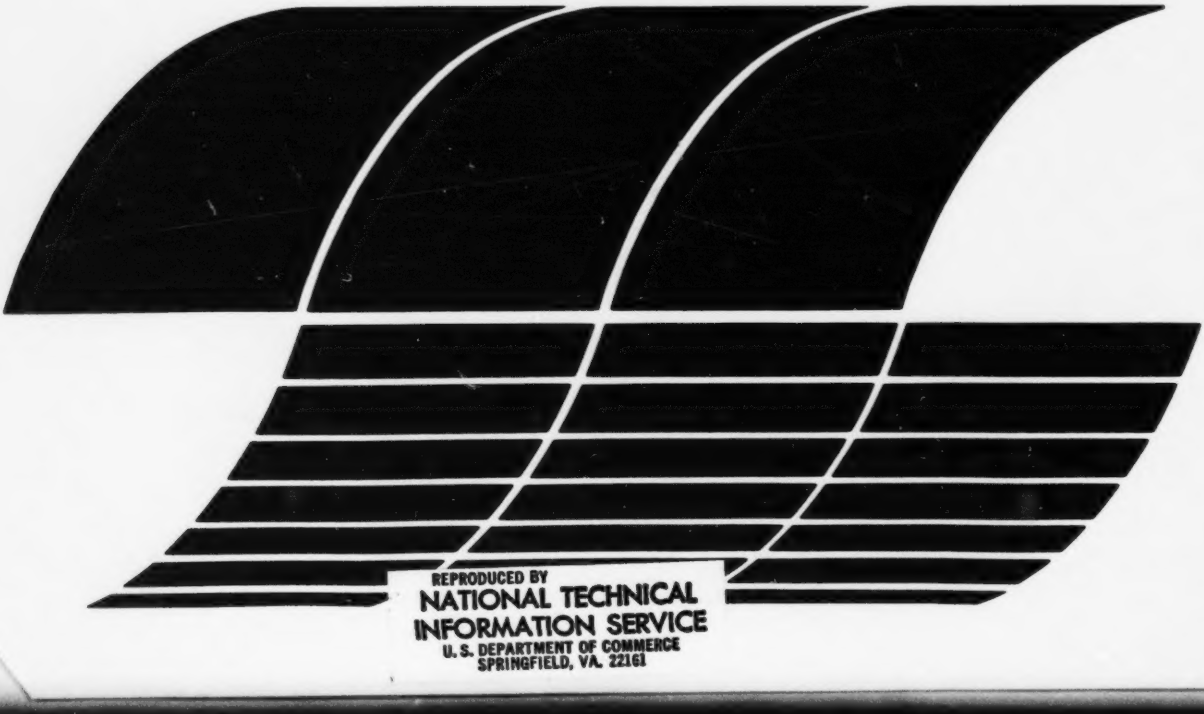
EPA-600/7-80-012d
March 1980

PB80-184765

EPA

Waste and Water Management for Conventional Coal Combustion: Assessment Report-1979
Volume IV.
Utilization of FGC Wastes

Interagency
Energy/Environment
R&D Program Report



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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-80-012d	2.	3. RECIPIENT'S ACCESSION NO. PB80-184765
4. TITLE AND SUBTITLE Waste and Water Management for Conventional Coal Combustion Assessment Report--1979; Volume IV. Utilization of FGC Wastes		5. REPORT DATE March 1980
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) C. J. Santhanam, R. R. Lunt, C. B. Cooper, D. E. Klimschmidt, I. Bodek, and W. A. Tucker (ADL); and C. R. Ullrich (Univ of Louisville)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Arthur D. Little, Inc. 20 Acorn Park Cambridge, Massachusetts 02140		10. PROGRAM ELEMENT NO. EHE624A
		11. CONTRACT/GRANT NO. 68-02-2654
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 9/77-8/79
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Julian W. Jones, Mail Drop 61, 919/541-2489.

16. ABSTRACT

The report, the fourth of five volumes, focuses on utilization of coal ash and FGD wastes. With increasing utilization of coal, generation of these wastes is expected to grow, but at a slower rate than generation, thus increasing the volume of wastes sent to disposal. Many uses for coal ash have been developed in three categories: as fill material; in the manufacture of cement, concrete, and pavements; and in miscellaneous uses such as ice control and blasting grit. In 1977, about 21% of the 61.6 million tons of coal ash generated was utilized. Current R and D projects on ash focus on understanding existing uses and developing new uses including mineral recovery. FGD wastes are not presently used in the U.S. Potential FGD utilization options may include use as gypsum substitutes, as fillers and soil conditioners, in cement and concrete manufacture, and construction of artificial reefs. Technical, environmental, and institutional barriers (the last being the most important) constrain utilization. Data gaps remain in quality requirements for using coal ash and FGD wastes in specific applications and understanding the instiutional constraints to utilization.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Water	Pollution Control	13B	07B
Coal	Flue Gases	Stationary Sources	21D	
Combustion	Cleaning	Flue Gas Cleaning	21B	13H
Assessments		Waste Utilization	14B	
Management			05A	
Utilization				

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 112
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

EPA-600/7-80-012d

March 1980

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by

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Contract No. 68-02-2654
Program Element No. EHE624A

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Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

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This First Annual R&D Report is submitted by Arthur D. Little, Inc. to the U. S. Environmental Protection Agency (EPA) under Contract No. 68-02-2654. The Report reflects the work of many members of the Arthur D. Little staff, subcontractors and consultants. Those participating in the study are listed below.

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We would like to note the helpful views offered by and discussions with Michael Osborne of EPA-IERL in Research Triangle Park, N. C., and John Lum of EPA-Effluent Guidelines Division in Washington, D. C.

Above all, we thank Julian W. Jones, the EPA Project Officer, for his guidance throughout the course of this work and in the preparation of this report.

ACKNOWLEDGEMENTS

Many other individuals and organizations helped by discussions with the principal investigators. In particular, grateful appreciation is expressed to:

Aerospace Corporation - Paul Leo, Jerome Rossoff
Auburn University - Ray Tarrer and others
Department of Energy - Val E. Weaver
Dravo Corporation - Carl Gilbert, Carl Labovitz, Earl Rothfuss and others
Electric Power Research Institute (EPRI) - John Maulbetsch, Thomas Moraski and Dean Golden
Environmental Protection Agency, Municipal Environmental Research Laboratory - Robert Landreth, Michael Roulier, and Don Sanning
Federal Highway Authority - W. Clayton Ormsby
IU Conversion Systems (IUCS) - Ron Bacskai, Hugh Mullen Beverly Roberts, and others
Louisville Gas and Electric Company - Robert P. Van Ness
National Ash Association - John Faber
National Bureau of Standards - Paul Brown
Southern Services - Reed Edwards, Lamont Larrimore, and Randall Rush
Tennessee Valley Authority (TVA) - James Crowe, T-Y. J. Chu, H. William Elder, Hollis B. Flora, R. James Ruane, Steven K. Seale, and others

CONVERSION FACTORS

English/American Units	Metric Equivalent
Length:	
1 inch	2.540 centimeters
1 foot	0.3048 meters
1 fathom	1.829 meters
1 mile (statute)	1.609 kilometers
1 mile (nautical)	1.852 kilometers
Area:	
1 square foot	0.0929 square meters
1 acre	4,047 square meters
Volume:	
1 cubic foot	28.316 liters
1 cubic yard	0.7641 cubic meters
1 gallon	3.785 liters
1 barrel (42 gals)	0.1589 cu. meters
Weight/Mass:	
1 pound	0.4536 kilograms
1 ton (short)	0.9072 metric tons
Pressure:	
1 atmosphere (Normal)	101,325 pascal
1 pound per square inch	0.07031 kilograms per square centimeter
1 pound per square inch	6894 pascal
Concentration:	
1 part per million (weight)	1 milligram per liter
Speed:	
1 knot	1.853 kilometers per hour
Energy/Power:	
1 British Thermal Unit	1,054.8 joules
1 megawatt	3.600×10^9 joules per hour
1 kilowatt hour	3.60×10^6 joules
Temperature:	
1 degree Fahrenheit	5/9 degree Centigrade

GLOSSARY

Cementitious: A chemically precipitated binding of particles resulting in the formation of a solid mass.

Fixation: The process of putting into a stable or unalterable form.

Impoundment: Reservoir, pond, or area used to retain, confine, or accumulate a fluid material.

Leachate: Soluble constituents removed from a substance by the action of a percolating liquid.

Leaching Agent: A material used to percolate through something that results in the leaching of soluble constituents.

Pozzolan: A siliceous or aluminosiliceous material that in itself possess little or no cementitious value but that in finely divided form and in the presence of moisture will react with alkali or alkaline earth hydroxide to form compounds possessing cementitious properties.

Pozzolanic Reaction: A reaction producing a pozzolanic product.

Stabilization: Making stable by physical or chemical treatment.

ABBREVIATIONS

BOD	biochemical oxygen demand
Btu	British thermal unit
cc	cubic centimeter
cm	centimeter
COD	chemical oxygen demand
°C	degrees Centigrade (Celcius)
°F	degrees Fahrenheit
ESP	electrostatic precipitator
FGC	flue gas cleaning
FGD	flue gas desulfurization
ft	feet
g	gram
gal	gallon
gpd	gallons per day
gpm	gallons per minute
hp	horsepower
hr	hour
in.	inch
j	joule
j/s	joule per second
k	thousand
kg	kilogram
kCal	kilocalorie
km	kilometer
kw	kilowatt
kwh	kilowatthour
ℓ or lit	liter
lb	pound
M	million
m^2	square meter
m^3	cubic meter
mg	milligram
MGD	million gallons per day
MW	megawatt
MWe	megawatt electric
MWH	megawatt hour
μg	microgram
mil	milliliter
min	minute
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch absolute
scf/m	standard cubic feet per minute
sec	second
TDS	total dissolved solids
TOS	total oxidizable sulfur
TSS	total suspended solids
tpy	tons per year
yr	year

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1.0 INTRODUCTION

1.1 Purpose and Content

With increasing coal utilization in industrial and utility boilers, generation of coal ash (fly ash and bottom ash) and flue gas desulfurization (FGD) wastes, which together comprise flue gas cleaning (FGC) wastes, is expected to increase dramatically in the next twenty (20) years. Utilization will constitute a valuable element of an integrated FGC waste management program. Against the background of developing regulatory constraints pertaining to air and water pollution control and the rising cost of disposal, utilization may offer an attractive waste management alternative to disposal. Furthermore, with a large anticipated mineral deficit in the United States in the future, FGC wastes may present a potential source of minerals in the future.

This is the fourth volume in a five-volume report assessing technology for the control of waste and water pollution from combustion sources. This volume reports on the status of FGC waste utilization including both current commercial practice and ongoing resource and development programs.

The focus of this volume on utilization is the evaluation of the technical, economic, regulatory, and environmental aspects of ongoing technology development and commercialization of FGC waste utilization. FGD wastes considered in this report are primarily those from nonrecovery systems.

At present, utilization of FGC wastes in the United States is modest but growing. Many European countries and Japan utilize a higher proportion of the coal ash and FGD waste produced in these countries than does the United States. There are, of course, inherent differences in availability of raw materials and marketability which account for some of the differences. For some specific end-uses, there may be some technological advantages favoring higher levels of utilization abroad. However, in general, there are significant institutional factors which favor increased utilization abroad and hinder expansion of domestic utilization.

The review and assessment has involved two separate efforts as described below:

(1) Review of the data and information available as of December 1978 on the utilization of FGC wastes. The review is based upon published reports and documents as well as contacts with private companies and other organizations engaged in FGC utilization technology development. Much of the information has been drawn from the FGC waste utilization studies and technology development/demonstration programs sponsored by various agencies of the U.S. government including, the Federal Highway Administration, the Army Corps of Engineers, the Department of Energy (DOE), the Bureau of Mines, the Environmental Protection Agency (EPA) and the Electric Power Research Institute (EPRI).

(2) An assessment of ongoing work in waste characterization, identification of data and information gaps relating to waste utilization, and development of recommendations for potential initiatives to assist in closing these gaps.

Throughout this work, emphasis has been placed upon waste utilization by commercially demonstrated technologies and, where data are available, by technologies in advanced stages of development that are potentially capable of achieving commercialization in the United States in the near future.

1.2 Report Organization

This report:

- Presents an overview on coal ash (fly ash and bottom ash) utilization in commercial practice at present,
- Assesses R&D programs for coal ash and FGD waste utilization,
- Identifies some of the constraints on FGC waste utilization, and
- Presents an outline of related data and information gaps.

2.0 UTILIZATION OF COAL ASH

2.1 Introduction

Coal-fired utility and industrial boilers generate two types of coal ash--fly ash and bottom ash. (Economizer ash and mill rejects are lumped into the two major categories here.) Both constitute the non-combustible (mineral) fraction of the coal and the unburned residuals. Fly ash, which accounts for the majority of the ash generated, is the fine ash fraction carried out of the boiler in the flue gas. Bottom ash is that material which drops to the bottom of the boiler and is collected either as boiler slag or dry bottom ash, depending upon the type of boiler.

The total amount of coal ash produced is directly a function of the ash content of the coal fired. Thus, the total quantity of ash produced can range from a few percent of the weight of the coal fired to as much as 35%. The partitioning of ash between fly ash and bottom ash usually depends upon the type of boiler. Standard pulverized coal-fired boilers typically produce 80-90% of the ash as fly ash. In cyclone-fired boilers, the fly ash fraction is usually less. In some cases, bottom ash constitutes the majority of the total ash.

The technology of ash collection, the characteristics of the ash produced, and projection of waste generation are discussed in Volume 3. This volume provides a review of ash utilization, both current practices as well as potential utilization alternatives that have been or are being investigated.

Fly ash is the major source of particulate emissions from utilities and with increasing regulatory stringency has required major collection systems. Control of particulate emissions from pulverized-coal-fired steam generators is rapidly becoming a significant factor in the siting and public acceptability of coal-burning power plants. The particulate emission limit set by the EPA for large, new coal-fired boilers is 0.043 grams/10^6 joules (0.1 lb/10^6 Btu). Some states have requirements more restrictive than this.

Fly ash carried in the flue gas stream can be collected in a number of ways to meet the current particulate emission control limitations as noted above. Typical methods historically employed include mechanical collection, electrostatic precipitation, fabric filtration and wet scrubbing. However, the tightening regulatory requirements support two criteria for fly ash collection systems:

- The collector must be efficient in removing sub-micron size particulate matter. This criterion eliminates from consideration all mechanical collectors and many wet scrubber systems (if they are used alone). Mechanical collectors may, however, function as a first unit followed by a more efficient collector.
- The collector must be available commercially and be proven in a utility boiler application. This constraint eliminates, for the immediate future, many hybrid wet scrubber systems and novel collectors that are now under development. In the long run, however, it is conceivable that such advanced systems may be used at least in some instances.

Collection of bottom ash (or boiler slag) does not involve systems outside the boiler. The technology of bottom ash handling is discussed in Volume 2.

2.2 Current Utilization

2.2.1 Characteristics of Coal Ash

Detailed discussions and data on the physical and chemical characteristics of coal ash are presented in Volume 3. In this section, some of the salient characteristics affecting ash utilization are outlined.

The chemical composition of coal ash (bottom ash, fly ash, and slag) varies widely, in concentrations of both major and minor constituents. Table 2.1 shows a compilation of chemical composition of both fly ash and bottom ash from the firing of a wide range of different coals. The principal factor affecting the variation in the composition is the variability in the mineralogy of the coal. However, differences in composition can exist between fly ash and bottom ash (or boiler slag) generated

Table 2.1

Range of Coal Ash Compositions

Major Constituents (wt %)	
Silica (as SiO_2)	25 - 60
Alumina (as Al_2O_3)	10 - 30
Ferric Oxide (as Fe_2O_3)	5 - 40
Lime (as CaO)	0.5 - 25
Magnesia (as MgO)	0.2 - 8.0
Potassium Oxide (as K_2O)	0.1 - 4.0
Sodium Oxide (as No_2O)	0.1 - 4.0
Titanium Dioxide (as TiO_2)	0.5 - 2.5
Sulfur Trioxide (as SO_3)	0.2 - 20
Carbon and Volatiles	ND - 2

Source: [1, 2]

from the same coal due to differences in the degree of pulverization of the coal prior to firing, the type of boiler in which the coal is fired, and the boiler operating parameters and combustion efficiency. Regardless of the type of ash (either fly ash or bottom ash), more than 80% of the total weight of the ash is usually made up of silica, alumina, iron oxide, and lime. It should be noted that the compositional breakdown shown in Table 2.1 reflects only the elemental breakdown of the constituents reported as their oxides and not necessarily the actual compounds present.

The physical properties of fly ash vary with the type of coal fired, the boiler operating conditions, and the type of fly ash collector employed. A mechanical collector, which generally removes only the heaviest fly ash fraction, produces a relatively coarse material with the consistency of a fine sand. In contrast, the ash removed in an electrostatic precipitator is usually finer, with silt-like grading. The range of specific gravities of fly ash depends upon particle size distribution and fly ash composition; however, specific gravities typically range from approximately 1.9 to 2.7. A small portion of the fly ash (<4%) consists of cenospheres (hollow spheres) which have an apparent density less than water. Bulk densities of fly ash, because of the variations in specific gravity and particle size distribution, vary greatly. Bulk densities of fly ash, therefore, vary greatly, although the typical range for fly ash compacted at optimum bulk density would be 110-135 lb/ft^3.

An important property of coal fly ash is its pozzolanic activity. Pozzolanic activity in fly ash, either due to contained lime or through the addition of lime, causes the fly ash to aggregate and harden when moistened and compacted. Because of the presence of pozzolanic activity in some fly ashes, the engineering properties of fly ash vary greatly. In general, untreated fly ash (that to which lime has not been intentionally added) exhibits engineering properties similar to soils of equivalent particle size distributions. Permeabilities of compacted fly ash samples generally range from 5×10^{-5} cm/sec to 5×10^{-6} cm/sec. Treatment of pozzolanic fly ashes with lime can result in significant increases in compressive strength and increases in permeability (depending upon the amount of lime, the water content, curing time, and degree of compaction).

Bottom ash can be collected either dry or in a molten state, in which case it is generally referred to as boiler slag. Dry-collected bottom ash is heavier than fly ash, with a larger particle size distribution. Since it has a similar chemical composition to that of fly ash, it behaves similarly, although pozzolanic activity is usually somewhat less in bottom ash.

Boiler slag is a black glassy substance composed chiefly of angular or rod-like particles, with a particle size distribution ranging from fine gravel to sand. Boiler slag is porous, although not of so great a porosity as dry bottom ash. It is generally less reactive in terms of its pozzolanic properties than either dry bottom ash or fly ash.

2.2.2 Current Utilization

Numerous uses for coal ash have been developed, both here in the United States and abroad. In 1977, total U.S. generation of coal ash was 61.6 million metric tons, of which 12.7 million metric tons were utilized* [3]. Data on utilization of coal ash for some selected years are presented in Table 2.2 Although the three types of coal ash (fly ash, bottom ash, and boiler slag) are interchangeable in some circumstances, they have historically served different markets.

Commercial utilization of coal ash is expected to increase in the United States, continuing the trend presented in Table 2.2. The increasing reliance on coal as a utility fuel with attendant increases in ash production may result in the percent of utilization being unchanged or even decreasing despite efforts to promote ash utilization through increased market visibility and technological development. Preliminary projections on generation of coal ash and FGD wastes are presented in Volume 3. Tightening environmental control regulations concerning disposal

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*"Utilized" in this sense refers to fly ash which is used as a substitute for some other material. Particularly in landfill applications (e.g., mine subsidence, fill, etc.) the distinction between utilization and disposal is often unclear. National Ash Association (NAA) statistics on utilization include material which is removed at no cost (or credit) to the utility and material which is removed from the utility disposal site. Federal Power Commission (FPC), on the other hand, includes only that material which is sold.

Table 2.2

Commercial Utilization of Coal Ash in the United States
Millions of Metric Tons (Millions of Short Tons)

	1966[a]	1974	1975	1976	1977
Ash Collected					
Fly Ash	15.5 (17.1)	36.7 (40.4)	38.5 (42.3)	38.9 (42.8)	44.1 (48.5)
Bottom Ash	7.4 (8.1)	13.0 (14.3)	11.9 (13.1)	13.0 (14.3)	12.8 (14.1)
Boiler Slag		4.4 (4.8)	4.2 (4.6)	4.4 (4.8)	4.7 (5.2)
Total Ash Collected (Tons x 10^6)	229 (25.2)	54.1 (59.5)	54.5 (60.0)	56.3 (61.9)	61.6 (67.8)
Ash Utilized					
Fly Ash	1.3 (1.4)	3.1 (3.4)	4.1 (4.5)	5.2 (5.7)	5.7 (6.3)
Bottom Ash	1.5 (1.7)	2.6 (2.9)	3.2 (3.5)	4.1 (4.5)	4.2 (4.6)
Boiler Slag		2.2 (2.4)	1.6 (1.8)	2.0 (2.2)	2.8 (3.1)
Total Ash Utilized (Tons x 10^6)	2.8 (3.1)	7.9 (8.7)	8.9 (9.8)	11.3 (12.4)	12.7 (14.0)
Percent of Ash Utilized					
% Fly Ash	7.9	8.4	10.6	13.3	13.0
% Bottom Ash	21.0	20.3	26.7	31.5	32.6
% Boiler Slag		50.0	40.0	45.8	60.0
Percent of Total Ash Utilized	12.1	14.6	16.4	20.0	20.7

[a] First year that data were taken.
Source: [3]

of wastes and constraints on land availability in some areas, however, would continue to impact utilization or disposal of FGC wastes. In particular, as regulations under the Resource Conservation and Recovery Act of 1976 (RCRA) become clearer, the impact of this key legislation on utilization would become better defined. At present, the utility by-product utilization industry is concerned about potential negative impact on utilization due to:

- Special waste category, and
- The effect of "use constituting disposal" issues.

A comparison of utilization data for 1971, 1976, and 1977 is presented in Table 2.3. Annual total ash utilization is presented in Table 2.4. Total ash utilization historically has been increasing from a low of 2.8 million metric tons in 1966 to a high of 12.7 million metric tons in 1977. However, it is difficult to draw conclusions about the trends in individual end-use categories; survey coverage has been increasing over the years, the end-use markets listed have been expanded, and about 35% of total consumption is in poorly defined or unknown categories.

Based on the available data, the following conclusions can be reached. Fly ash and bottom ash utilization has been increasing, from 2.8 million metric tons in 1966 to 4.4 million metric tons in 1971, to 9.9 million metric tons in 1977. Utilization of boiler slag has fluctuated but has not shown a discernible trend, staying around 2.7 million metric tons per year. A possible explanation for some of the variation is that boiler slag (and sometimes bottom ash) is normally sold out of stockpile; therefore, sales in any given year have little relation to production. Fill usage, the largest single end-use market, has been relatively constant over the years. Usage in cement and cement products has been increasing gradually as has the use of slag in blast grit/roofing.

Table 2.3

Ash Utilization

Millions of Metric Tons (Millions of Short Tons)

Use	Fly Ash 1971	Fly Ash 1976	Fly Ash 1977	Bottom Ash 1971	Bottom Ash 1976	Bottom Ash 1977	Boiler Slag 1971	Boiler Slag 1976	Boiler Slag 1977
A. Commercial Utilization									
1. Mixed with raw material before forming cement clinker	.09(0.10)	-	.40(0.44)	-	-	-	.08(0.09)	-	.08(0.09)
2. Mixed with cement clinker or mixed with pozzolan cement (I-P)	.018(0.02)	.46(0.51)	.29(0.32)	-	.08(0.09)	.08(0.09)	-	.036(0.04)	-
3. Cement replacement	.39(0.43)	.83(0.91)	1.43(1.58)	.036(0.04)	-	-	.07(0.08)	-	-
4. Lightweight aggregate	.16(0.18)	.10(0.11)	.12(0.13)	.009(0.01)	-	.13(0.14)	-	-	-
5. Fill material for roads, construction sites, etc.	.33(0.36)	1.34(1.48)	1.14(1.26)	.48(0.53)	(0.00)	.83(0.92)	2.38(2.63)	-	.23(0.25)
6. Stabilizer for road bases, parking areas, etc.	.036(0.04)	.21(0.23)	.17(0.19)	.007(0.008)	.62(0.68)	.21(0.23)	0.45(0.05)	.20(0.22)	.05(0.06)
7. Asphalt filler	.14(0.15)	.21(0.23)	.12(0.13)	.003(0.003)	-	-	.07(0.08)	-	-
8. Ice control	-	-	-	-	.41(0.45)	.92(1.01)	-	.10(0.11)	.36(0.40)
9. Blast grit/roofing	-	-	-	-	-	-	-	1.10(1.21)	1.35(1.49)
10. Miscellaneous	.09(0.10)	.46(0.51)	.17(0.19)	.44(0.48)	.82(0.90)	.37(0.41)	.39(0.43)	.28(0.31)	.62(0.68)
B. Ash Removed from Plant Site (at no cost to utility but not covered in categories listed above)	1.70(1.87)	.26(0.29)	.40(0.44)	.49(0.54)	.94(1.04)	.71(0.78)	.34(0.38)	.16(0.18)	.11(0.12)
C. Ash Removed to Disposal Areas (at company expense)	-	1.29(1.43)	1.49(1.64)	-	1.14(1.26)	.92(1.01)	-	.12(0.13)	(0.00)
TOTAL	2.94(3.25)	5.17(5.7)	5.7(6.3)	1.46(1.61)	4.08(4.50)	4.17(4.60)	3.39(3.74)	2.0(2.20)	2.81(3.1)

Source: [3, 4, 5]

Table 2.4

Total Ash Utilized

Millions of Metric Tons (Millions of Short Tons)

Year	Fly Ash	Bottom Ash	Boiler Slag	Total
1966	1.3 (1.4)	1.5 (1.7)	- (-)	2.8 (3.1)
1967	1.3 (1.4)	2.1 (2.3)	- (-)	3.4 (3.7)
1968	1.7 (1.9)	1.6 (1.8)	1.4 (1.5)	4.7 (5.2)
1969	1.7 (1.9)	1.8 (2.0)	0.9 (1.0)	4.4 (4.9)
1970	2.0 (2.2)	1.6 (1.8)	1.0 (1.1)	4.6 (5.1)
1971	3.0 (3.3)	1.5 (1.6)	3.4 (3.7)	7.9 (8.6)
1972	3.3 (3.6)	2.4 (2.6)	1.2 (1.3)	6.9 (7.5)
1973	3.5 (3.9)	2.1 (2.3)	1.6 (1.8)	7.2 (8.0)
1974	3.1 (3.4)	2.6 (2.9)	2.2 (2.4)	7.9 (8.7)
1975	4.1 (4.5)	3.2 (3.5)	1.6 (1.8)	8.9 (9.8)
1976	5.2 (5.7)	4.1 (4.5)	2.0 (2.2)	11.3 (12.4)
1977	5.7 (6.3)	4.2 (4.6)	2.8 (3.1)	12.7 (14.0)

Source: [6]

Important commercial markets for coal ash in the United States include the manufacture of cement and concrete, use as landfill and soil stabilizer, use in blasting (abrasion) compound, and for ice control. For the purposes of this discussion, utilization of coal ash has been broadly broken down into three end-use categories:

- Fill material,
- Manufacture of cement, concrete, and pavements, and
- Miscellaneous.

Each of these categories is discussed in the following section.

2.3 Ash Utilization as Fill Material

The largest use of coal ash historically has been as fill material in construction, either as a replacement for common borrow, or to stabilize poor soils in fly ash/soil mixtures or lime/fly ash/soil mixtures. Ash and ash/soil mixtures can be more economical than common borrow where the hauling distance is relatively short, if there is a lack of suitable borrow material near the construction site, or if other material is not available locally for environmental reasons.

2.3.1 Borrow Substitute

Coal ash can offer distinct technical advantages as a fill material because of its low density and significant strength (Table 2.5). In situations where filling is necessary on relatively weak subsoils, natural materials can produce excessive settlement. Traditional materials are available for use as a fill in these situations, but because of its low density, fly ash can represent a more economical solution since it reduces the overburden weight.

A significant characteristic of fly ash is its strength. Well-compacted fly ash has been shown to exhibit strengths comparable to those for soils normally used in earthfill operations. Tests indicate that most fly ashes have shear strength parameters which would make them stable and strong construction materials for highway embankments and other light load-bearing fills [7]. In addition, many fly ashes possess self-hardening properties in the presence of moisture, which can result in the development of shear strengths in excess of those encountered in many soils. The addition of lime or cement can induce hardening in fly ashes which may not self-harden alone. Significant increases in shear strength parameters can

Table 2.5

Ash Utilization as Fill

	Borrow Material	Stabilized Fill
Ash Consumer	Contractor	Fill Supplier
Ash Requirements	a) Particle size distribution important b) Fly, bottom, or slag	a) Particle size distribution important b) Must be <10% water soluble c) Fly, bottom, or slag
Technical Benefits	a) Lighter than common fill b) Erosion can be problem c) Dusting can be problem d) Water slippage can be problem	a) Can be stronger than common fill
Direct Savings	Site specific	Site specific
User Benefits	Ash fill can be useful to reduce load on base	Stabilized fill can be stronger
Economic Benefits	Site specific	Site specific

Source: Arthur D. Little, Inc.

be realized in relatively short periods of time and, if taken into consideration in design, can represent a distinct technical advantage over other construction fill materials. Addition of lime (or alternatives allowing the self-hardening process in some fly ashes to proceed) is called stabilization.

Coal ash, if not properly stabilized, is subject to freeze/thaw failure, erosion, and leaching problems (if not properly applied).

- The grain-size distribution of most fly ashes makes them similar to frost susceptible soils. Frost susceptibility is influenced by particle size distribution, size, mineralogical composition, strength, and permeability [7] but cannot be satisfactorily correlated with a single parameter of strength or permeability and no specifications have been developed for this use. Testing is required for each individual fly ash if the ash is to be used in regions where it is exposed to freezing temperatures.
- Unprotected, compacted slopes of fly ash are subject to erosion by surface runoff or wind. It is necessary to protect these surfaces by pavement, topsoil and seeding, asphalt emulsion, or stabilization with cement.
- Fly ash contains water soluble components in the range of 1-7% by weight [8, 9, 10]. Leaching of these components can occur by surface runoff or infiltration (percolation). Leachates from fly ashes are of environmental concern particularly if the leachate contains trace metals. Potential pollution of ground and surface water from such leachates can be minimized by pavement or liners, topsoil, vegetative cover, or drains.

Fly ash, bottom ash, and boiler slag can all be utilized as borrow material. However, fly ash and bottom ash are used in this duty more frequently; boiler slag often can be used in more valuable ways. When used by itself, ash can offer an economic advantage in areas where borrow materials are not easily available. However, except for this be realized in relatively short periods of time and, if taken into consideration in design, can represent a distinct technical advantage over other construction fill materials. Addition of lime (or alternatives allowing the self-hardening process in some fly ashes to proceed) is called stabilization.

Coal ash, if not properly stabilized, is subject to freeze/thaw failure, erosion, and leaching problems (if not properly applied). The grain-size distribution of most fly ashes makes them similar to frost susceptible soils. Frost susceptibility is influenced by particle size distribution, mineralogical composition, strength, and permeability [7] but cannot be satisfactorily correlated with a single parameter of strength or permeability, and no specifications have been developed for this use. Testing is required for each

- individual fly ash if the ash is to be used in regions where it is exposed to freezing temperatures.
- site where unprotected, compacted slopes of fly ash are subject to erosion by surface runoff or wind. It is necessary to protect these surfaces by pavement, topsoil and seeding, asphalt emulsion, or stabilization with cement.
- fly ash containing water soluble components in the range of 1-7% by weight [8, 9, 10]. Leaching of these components can occur by surface runoff or infiltration (percolation), particularly if the leachate contains trace metals. Leachates from fly ashes are of environmental concern. Potential pollution of ground and surface water from such leachates can be minimized by pavement or liners, topsoil, vegetative cover, or drains.

Fly ash, bottom ash, and boiler slag can all be utilized as borrow material. However, fly ash and bottom ash are used in this duty more frequently; boiler slag often can be used in more valuable ways. When used by itself, ash can offer an economic advantage in areas where borrow materials are not easily available. However, except for this special circumstance, and those instances where it offers a distinct technical advantage, ash is not generally used for landfill because of the wide availability of natural fill materials.

2.3.2 Soil Stabilization

Some of the problems associated with unstabilized ash fill can be overcome (or at least lessened) if the fly ash is used with soil in a stabilized mixture. These types of mixtures have been used commercially, especially in England but have not been used extensively in the United States.

Soil stabilization generally refers to the physical and/or chemical methods used to improve natural soils or soil-aggregates for use in some engineering applications. Soil stabilization is used predominantly in the construction of roadways, parking areas, runways, and foundations. Soil stabilization can eliminate the need for expensive borrow materials, expedite construction by improving particularly wet or unstable subgrade, effect savings in pavement thicknesses by improving subgrade conditions, and permit the substitution in the pavement cross-section of low-cost materials for conventional and less economical materials.

The low cost of fly ash and its excellent pozzolanic properties make lime/fly ash stabilization more advantageous than lime or cement stabilization in many cases. Depending on the soil type, lime/fly ash stabilization can produce greater strengths and improved durability compared with lime stabilization. In locations where lime is cheaper than cement, lime/fly ash stabilization can often produce material of comparable long-term strength and durability at a reduced cost when compared to cement stabilization.

The suitability of a particular fly ash for stabilization can be determined by subjecting various mixtures of the fly ash and the soil to be stabilized to a suitable laboratory testing program. The American Society for Testing and Materials (ASTM) Specification C 593 places two constraints on fly ash to be used in lime/soil mixtures. The requirements, which pertain to maximum allowable water soluble fraction and to gradation, are outlined in Table 2.6.

Table 2.6

ASTM C 593 Requirements Pertaining to Fly Ash for Use With Lime/Soil Mixtures

Item	Criteria %
Water Soluble Fraction	Max. 10
Fineness-amount retained when wet sieved:	
No. 30 (595 μ) sieve	Max. 2.0
No. 200 (74 μ) sieve	Min. 30.0

Source: [14]

An important physical indicator of stabilization potential is the fineness, or specific surface, as determined in accordance with ASTM C 311-68. The finer the fly ash particles, the greater the rate of pozzolanic reaction. High carbon content (measured as a loss-on-ignition in accordance with ASTM C 311-68) tends to inhibit the pozzolanic reactivity of a fly ash as well as decrease its density. High calcium oxide (CaO) is usually indicative of the presence of substantial amounts of free lime, which not only may have a beneficial effect on a soil's physical properties but which reacts with the siliceous and aluminous compounds in the fly ash to produce cementation.

Stabilization of soils with fly ash alone is still in the developmental stage. This method is most successful when fly ash with self-hardening properties is used. In general, fly ash of this type has a high free lime content and low carbon content, as measured by loss-on-ignition.

2.3.3 Market Characteristics and Economics

The available literature indicates that, to date, there have been no significant problems with lime/fly ash/soil mixtures when properly placed [7, 11, 12]. The Federal Highway Administration (FHWA) has done extensive research in this end-use application and has approved its use in highway construction in a variety of ways [13].

The market size for fill material is quite large. However, the use of coal ash in this application is limited. Borrow material usually is available and costs about $2 to $3 per ton at the borrow site ; cost of transportation is added to this base cost. The latter usually is the limiting factor in the cost of borrow material. Since, borrow sites usually can be developed in reasonable proximity to point of use (as a fill), the use of coal ash in this application is normally limited to specific cases where the characteristics of the ash merit such consideration or where borrow material is not readily available.

2.4 Ash in Cement and Concrete

The use of coal ash in cement and concrete products is the second largest and one of the more visible uses for ash. Ash can be used in a variety of ways in this end-use. Some options on using ash in concrete products are presented in Figure 2.1. It can be added to the raw materials and processed with the cement; it can be added to the finished cement and blended, either at the production facility, at a readymix plant, or at the construction site; or lime can be added to coal ash to take advantage of the inherent pozzolanic properties of the ash. Each use has advantages and disadvantages some of which are summarized in Table 2-7.

2.4.1 Ash in Cement

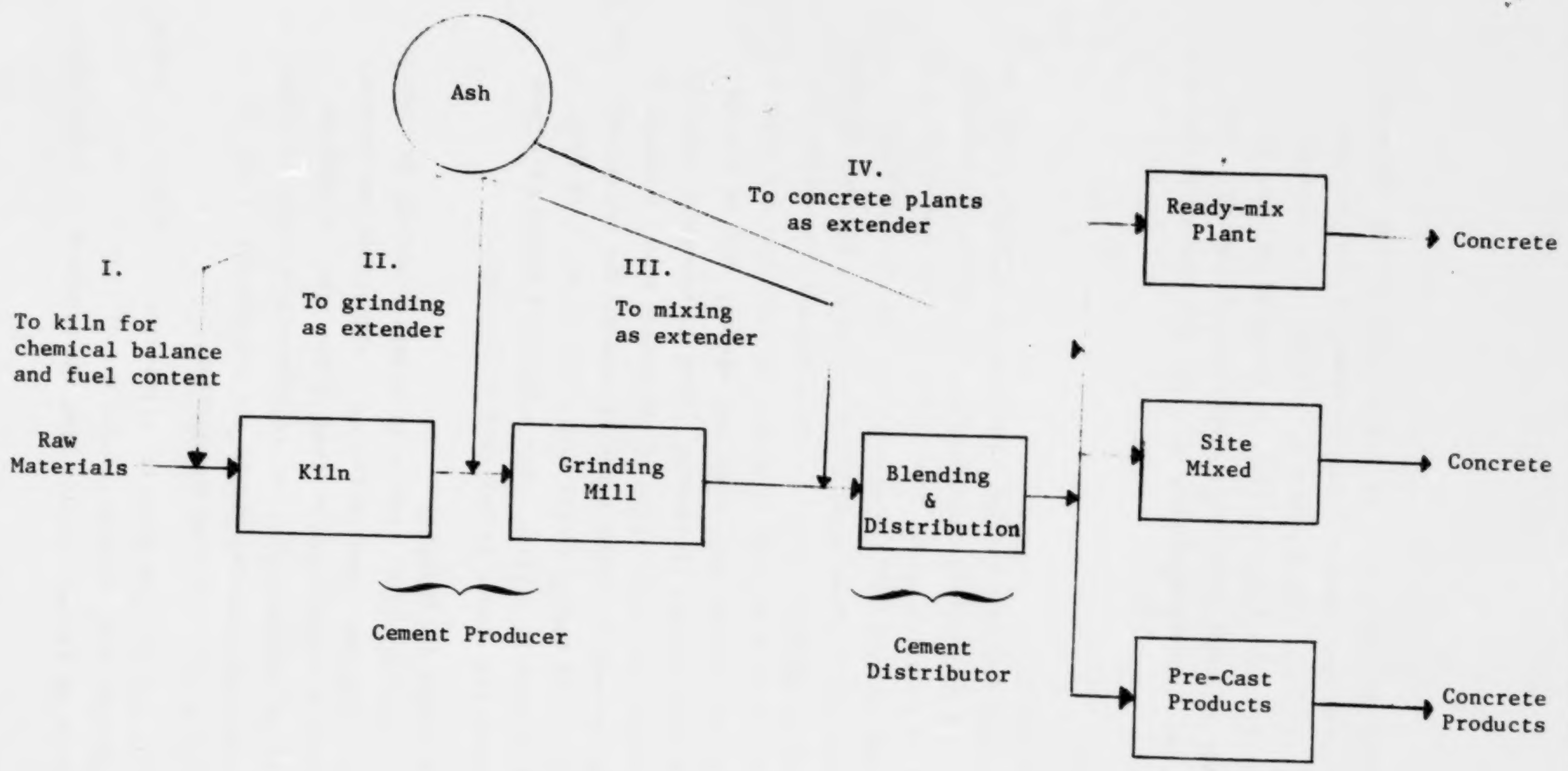
2.4.1.1 Cement Production

Cement manufacture involves burning lime, silica, alumina, iron, and magnesia in a kiln and pulverizing the product. The cement reacts with water to bond rock or sand and gravel into concrete. The key material is lime (CaO); important sources include cement rock (impure limestone), limestone, marl, and shell. When alumina and silica are not present with the lime in sufficient amounts, secondary raw materials are needed to supply the balance. Natural sources of silica include sand and quartz; alumina sources include shales, mud, clay, and wastes, such as fly ash, slag, and red muds from bauxite processing. Iron is sometimes added in small amounts to adjust the composition of the cement mix. Although composition varies between different types of cement, the raw material blend is generally 73-78% $CaCO_3$, 12-17% SiO_2, 2-5% Al_2O_3, 1-3% FeO_3, 1-5% $MgCO_3$, and less than 1% alkalis. For a detailed review of cement production processes, the reader is referred to [15, 54].

2.4.1.2 Ash As A Cement Raw Material

Ash can substitute for other sources of alumina, silica, or iron in cement production. Coal ash compares favorably with other raw material sources for blending with limestone as feed to the kiln. A uniform quality fly ash is an important chemical requirement in order to avoid frequent costly and time-consuming checks and adjustments of the raw mixture to maintain proper kiln feed composition.

The use of fly ash as a raw material eliminates the mining, crushing, and pulverizing process that is required for use of clay and shale. An additional advantage of fly ash results from the presence of carbon which


Ash
I.
To kiln for
chemical balance
and fuel content
II.
To grinding
as extender
III.
To mixing
as extender
IV.
To concrete plants
as extender
Raw
Materials
Kiln
Grinding
Mill
Blending
&
Distribution
Cement Producer
Cement
Distributor
Ready-mix
Plant
Site
Mixed
Pre-Cast
Products
Concrete
Concrete
Concrete
Products

Source: Arthur D. Little, Inc.

Figure 2.1 Coal Ash Utilization in Concrete Products

Table 2.7

'Ash Utilization in Cement and Concrete

Ash Consumer	I. Cement Producer	II. Cement Producer	III. Cement Distributor	IV. Readymix Supplier, Concrete User
Ash Requirements	a) High carbon okay b) Particle size unimportant	a) Low carbon required b) Particle size unimportant c) Fly, bottom, or slag	a) Low carbon required b) Particle size important c) Must meet ASTM cement specifications d) Fly ash only	a) Low carbon required b) Must meet end-use (performance) specifications c) Particle size importan d) Fly ash only
Technical Benefits	a) Reduces raw material consumption	a) Reduces kiln energy b) Reduces raw materials	a) Reduces kiln energy b) Reduces raw material c) Reduces grinding energy	Reduces portland cement consumption
Direct Savings	Slight--some secondary raw material	Portion of kiln energy	Portion of kiln and grinding energy	Approximately 45 kg (100 lb) of cement per m^3 concrete
Benefit To User	-	a) Improved workability b) Decreased heat of hydration c) Improved surface finish d) Increased long-term strength e) Increased resistance to sulfate attack		
Economic Benefits	-	% of cement manufacturing cost	% of cement manufacturing cost	% of concrete selling price

Source: Arthur D. Little, Inc.

can supply fuel for firing in the kiln, and, since it contains no water or crystallization which must be driven off as do clay and shale, the heating requirements are reduced. However, apart from the potential economic advantage, coal ash has no technical advantage over other raw materials in this use.

2.4.1.3 Ash As A Cement Additive

Fly ash can be mixed with finished cement or interground with cement clinker. Fly ash added at either of these two points in the manufacturing process remains as fly ash and is thoroughly blended into the portland cement. The resulting material has essentially the same advantages in use as those obtained by adding fly ash to concrete mix (see Section 2.2.3.4).

Cement with fly ash additive must be marketed as a separate product and as such, separate handling, storage, stocking, etc., are involved. Unless the volume of such fly ash cement is adequate, this utilization of fly ash would have economic demerits. Also, the blending of the two materials requires careful control to ensure uniformity of the cement.

It should be noted that the product specifications for the use of ash in concrete are quite different from that for the use of ash in cement. It is possible to use different clinkers for these two different uses.

2.4.2 Ash in Concrete

The ingredients used to produce conventional portland cement concrete are portland cement, water, gravel or stone, sand, and a variety of chemicals to either increase the air content of the concrete or reduce the amount of water required for the proportioning of the concrete mixture, or modify the settling characteristics of the cement. The amounts of each of the ingredients affect the concrete properties. ASTM Specification C 618-77 [19] for the use of fly ash as a pozzolan in concrete manufacture classifies fly ash as derived from: 1) anthracite or bituminous coal or 2) lignite or subbituminous coal. The specifications cover combined percentages of silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3), maximum SO_3, maximum moisture content, maximum loss-on-ignition, maximum magnesium oxide (MgO) content, maximum sodium oxide (Na_2O) content, required particle fineness, pozzolanic activity index, soundness, and uniformity.

The use of fly ash as a raw material in the production of concrete serves two primary purposes:

- To supplement or replace fine aggregate and cement, and
- To improve properties of the concrete.

Coal ash is useful as aggregate replacement because of its pozzolanic nature. A pozzolan is a siliceous or alumino-siliceous material which is not cementitious in itself but which, in finely divided form and in the presence of moisture, reacts with alkali and alkaline earth products to produce cementitious products [16]. The pozzolanic reaction between fly ash and lime (cements) results in a material of substantial strength.

Among the improvements attributed to fly ash/concrete are improved pumpability, higher compressive strength (and long-term strength), better workability and finishability, and higher resistance to sulfates and alkali/aggregate reaction: use of fly ash in concrete decreases the heat of hydration, drying shrinkage, particle segregation, bleeding, permeability, and leaching [16, 17, 18].

Sulfate Resistance

There is strong evidence that blended cements tend to show higher resistance to sulfate attack than do portland cements [20]. Sulfate attack on concrete can lead to expansion of the cement with resultant catastrophic cracking/crumbling of the concrete. Concrete can be exposed to sulfate conditions from drainage water, groundwater, and seawater. While the actual mechanism is not fully understood, attack may result from reaction of soluble sulfates (e.g., from groundwater) with the calcium hydroxide and hydrated alumina in the cement to form gypsum and highly hydrated calcium aluminosulfate compounds having large specific volumes. Susceptibility to these reactions appears to be reduced in blended cements, possibly because of reactions between the calcium hydroxide and fly ash [17, 18, 20].

Alkali/Aggregate Reaction

The reaction between alkalis present in cement and certain types of stone aggregate used in concrete sometimes leads to the formation of highly hydrated alkali silicates [20]. The formation of these compounds can result in disruptive expansion of concrete. The mechanisms and kinetics of these reactions are not well understood and, depending on the nature of the aggregate and the exposure conditions, expansion may manifest itself at an early age or only after several years. Additions of fly ash to a cement or concrete can reduce the expansion due to this reaction but low alkali portland cements are more commonly used.

Improved Workability

Fly ash improves the workability of concrete by making it more plastic, decreasing particle segregation, and decreasing bleeding [16]. Normally, more water is required for making concrete when pozzolans have been added to the mix. Fly ash differs from most pozzolans in this respect. Concrete containing low-carbon (2%) fly ash generally requires less water than portland cement concrete [21]. However, work by ASTM Section C09.03.08 suggests that both carbon content and fineness influence the water requirements [22]; high carbon content does not raise water requirements, per se. Concretes with fly ashes containing an excess of about 2% carbon require proportionately more water than does standard concrete.

Heat of Hydration

Concretes containing fly ash have a lower heat of hydration than portland cement concrete. Consequently, they do not get as warm as equal amounts of portland cement concrete. For this reason, fly ash is used in much of the mass concrete construction in dams and spillways [18, 23]. Specifications exist for this use, and fly ash is proportioned according to the heat of hydration desired.

Strength

When ash is substituted for portland cement in concrete, the two products have different rates of strength gain and differences in the effects of curing temperature on strength gain may be substantial. The addition of small amounts (5-10%) of fly ash to Type 1 portland cement may improve the early strength of the concrete. Concrete containing greater amounts of fly ash may show less rapid gains in strength but higher ultimate strengths [20]. Mixes in which fly ash is substituted for cement on a one-for-one basis (to conform to water-cement ratio specifications) usually produce concrete that is weaker than no-ash concretes at ages up to 28 days.* Properly proportioned fly ash concrete mixes usually will produce concretes with 28-day strengths comparable to concrete without fly ash.

Freeze/Thaw Durability

In much of the country, concrete is subject to damage from repeated freezing/thawing cycles. When fly ash concrete is tested for freeze/thaw durability, inferior resistance has been observed, probably because the test is begun after a short curing period (i.e., less than 28 days) and does not allow for the lower rate of strength development of ash concrete. Freeze/thaw studies, when initiated after longer curing periods, have indicated that fly ash concrete develop strengths equivalent or superior to those of portland cement concrete and develop superior resistance to freezing and thawing [20]. Another factor involved in freeze/thaw durability is the air content. When fly ash concrete with an air content equal to that of conventional portland cement concrete is tested, it appears to have good freeze/thaw durability [24].

Disadvantages

Adequate quality control of the fly ash and proper system design are essential for effective utilization of ash in concrete. Lack of proper attention to quality control has been the cause of some problems.

The properties that make ash utilization in concrete desirable can also make handling difficult; easy flowability may cause problems in feeding and weighing the fly ash, and the fineness of fly ash can cause air pollution and other problems. Control of the fineness and other properties of the fly ash can pose problems. Uniformity of performance of a fly ash/cement depends on both the cement and the fineness and composition of the fly ash. Determination of the proportions for fly ash concrete is system-specific due to the variation in the physical and chemical properties of different ash materials.

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*Much readymixed concrete is required to meet 28-day minimum strength values.

Much of the concrete placed in the United States contains chemical admixtures which are used to regulate set times, entrain air or reduce water requirements [20]. Set regulation is used to extend the time available for finishing; air entrainment (production of small air bubbles in the cement) is used to improve resistance to freeze/thaw damage; decreased water requirements lead to a reduction in the porosity of the concrete which increases strength and chemical resistance. Cements containing fly ash contain variable amounts of carbon from incomplete combustion of the coal. Carbon adsorbs chemical admixtures and tends to diminish their effectiveness as well as making them difficult to predict.

2.4.3 Lime/Fly Ash/Aggregate Basic Courses

Lime/fly ash/aggregate (LFA) mixtures are blends of mineral aggregate, lime, fly ash and water. When combined in proper proportions and compacted to a high relative density with reasonable curing conditions, they gradually harden to produce high quality paving materials. A wearing surface is applied to the base course to protect the material from the abrasive effects of traffic, from weathering, and from water infiltration.

In addition to lime, stabilization (that is, pozzolanic reaction) of fly ash can be produced in a number of ways. In lime stabilization, lime is added directly to the fly ash, moisture is introduced, and the mixture is then compacted to facilitate the pozzolanic reaction. In cement stabilization, cement is added to the fly ash instead of lime; the cement hardens as well as releasing certain amounts of lime which react with the fly ash in a pozzolanic manner. Certain types of fly ash also contain substantial quantities of free lime which can harden fly ash without the external addition of lime or cement. This third process is known as self-hardening of the fly ash.

LFA mixtures have been used extensively abroad. To a lesser extent, LFA mixtures have been used in the United States. Approximately 500,000 to 1,000,000 tons per year are typical quantities placed for the last 10 or more years of IUCS's "Poz-O-Pac" roadbase, and considerable quantities of similar materials have been placed by others [25]. Against the background of total roadbase construction, these are not large; however, the potential use is significant.

2.4.4 Ash As Aggregate Substitute

Aggregates are the largest single mined commodity in the United States. However, the supply is decreasing and in certain areas of the country (particularly some industrial or metropolitan areas) demand for natural mineral aggregates for construction purposes exceeds locally available supplies. With increasing energy costs and consequent cost increase for transportation, there is an economic incentive to find suitable replacement aggregates in the local area rather than transport them over large distances. Utilization of fly ash as a lightweight aggregate is feasible, particularly in many parts of the country where there are shortages and coal-fired generating plants in the same area. There are few significant technical limitations to the use of fly ash for lightweight aggrgate.

Bottom ash has also found use as a lightweight aggregate in construction and as aggregate in roadbase construction. Extensive testing has been done on the physical and structural characteristics of bottom ash and boiler slag for various purposes in road construction [26].

The increasing acceptance of coal ash as aggregate materials and the development of appropriate specification for its use may provide an outlet in those areas of the country where large amounts of coal-fired wastes will be generated.

2.4.5 Market Characteristics and Economics

While a large body of data has been accumulated on specific uses of fly ash in cement, concrete, and in roadbase construction, generic economic data are not available. Economics of ash utilization in this category are very site- and system-specific; a case-by-case evaluation is required.

The profitability of using fly ash depends upon where in the cement production process it is substituted, its quality, its cost relative to cement, the transportation distance involved, the value accrued from any technical advantages, e.g., less pouring time and less finishing time than for standard concrete, and the expense for additional equipment to handle fly ash at the cement plant.

Ash can be substituted as a raw material in the cement kiln feed, as an additive with clinker in the grinder feed, as an additive with cement at a mixing plant (sold as cement), or as an additive in concrete at a readymix plant. The profitability of using ash at the cement producer is probably minimal except in special cases. As a raw material additive, ash imparts few technical advantages and has no significant cost advantages except in cases where other materials are not available. As an additive to clinker for grinder feed, ash would save a proportional fraction of the kiln energy. Technical advantages may result from ash use in this application, however the cost savings would probably not offset the increased capital expenditure for ash-handling equipment.

Ash utilization as an additive to cement or concrete can potentially result in significant cost advantages. Previous work has indicated that the cost advantage to using ash is related to the transportation distance for a given set of conditions (e.g., plant size, cement cost, transportation cost). This impact will be very site-specific and vary from location to location. For example, in the west where there is a lack of natural pozzolans, ash could be transported great distances and still be an economically usable pozzolan. Conversely, in the east, transportation costs can offset any cost advantages quite rapidly. Work just being completed (see R&D-DOE) indicates that ash utilization usually has an economic advantage but that institutional factors have hindered further utilization of ash. The latter are discussed later in Section 5 of this volume.

The profitable marketing of ash in cement/concrete cannot be based on cost considerations alone. The marketplace is significantly influenced by a variety of non-economic factors which can easily outweigh any perceived cost advantages.

In order to use fly ash in cement economically, it may be necessary for the cement plant to be located near a coal-burning utility. For example, clay or shale is stripped to obtain underlying limestone for a cement plant. That clay or shale will often be used in the raw batch even if fly ash is available nearby. The fineness and flow characteristics of fly ash require handling, transportation, and dust collection equipment different from those for the stripped clay or shale. If fly ash is to be used, considerable capital investment in cement plant design and equipment must be committed to a fly ash raw material source. Guarantees as to quantity and quality of fly ash that will be available for future use will be essential for a cement manufacturer to commit himself to fly ash. Quality control and long-term guarantees are key requirements to increase utilization of ash in any premium use.

2.5 Ash in Miscellaneous Uses

Coal ash has been used in a variety of other applications in the United States, but these are generally on a smaller scale than the uses described earlier. However, three specialized uses are important and presented in Table 2.8.

A significant amount of bottom ash (0.92 M tons in 1977) and boiler slag (0.36 M tons) are used for ice control on winter roads. Such materials are often provided at no cost or at nominal cost to the user by the utilities. Little generic information is available on this, but it would seem to be inherently site-specific. Broadly, there are some environmental advantages in using ash in preference to salt in this use in addition to technical and economic benefits. (See Table 2.8.)

Almost half (1.35 M tons in 1977) of all boiler slag is consumed as blast grit or roofing granules. Again, it would appear to be a site-specific use depending upon the availability of alternative materials.

A potential end-use for fly ash which could consume significant quantities of ash in the future, is in production and/or fixation/stabilization of FGD waste. The amount and type of ash in FGD waste can influence both the scrubber operation and the disposal operation. In certain instances, especially with high CaO western coals, the alkalinity

Table 2.8

Ash Utilization in Miscellaneous Uses

	Blast Grit/ Roofing	Ice Control
Ash Consumer	Manufacturer	Highway Department
Ash Requirements	a) Only boiler slag b) Size restriction	a) Bottom ash or boiler slag
Technical Benefits	Unknown	Low solubility
Direct Savings	Equal to cost differential	Equal to cost differential
User Benefits	-	-
Economic Benefits	-	-

Source: Arthur D. Little, Inc.

in the ash can be substituted for some or all of the scrubber reagent. Fly ash also can aid in disposal because dewaterability is improved, the fly ash acts as a pozzolan to help "fix" the waste (especially when there is free lime), and fly ash oxidizes calcium sulfite to sulfate. Processes are currently being commercially marketed for the fixation of FGD waste which utilize fly ash; these are discussed in Volumes 3 and 5. Fixation of FGD wastes by fly ash and lime usually results in a soil-like material subject to less leaching due to lower permeability and occupying less volume due to increase in final bulk density compared to separate disposal of these materials.

2.6 Ash As A Mineral Resource

In addition to the uses discussed above, a variety of potential uses for coal ash have been proposed [6, 11, 16, 71]. These have included:

- Mineral recovery (alumina, iron, magnetite),
- Mineral wool,
- Mineral aggregate, and
- Filler (for plastics, rubber, etc.) and many others.

Some of these uses are currently being commercialized in the United States; others have been or are being used abroad, and some are still under development. However, these applications require technical breakthroughs or fundamental institutional or economic changes. An example of a future potential use requiring technological breakthrough for economic competitiveness is mineral recovery from fly ash. Some research has been done and methods for extracting alumina, magnetite or other minerals do exist. However, at present, these processes are either not capable of competing with more established processes or the market does not exist because of a readily available alternate supply of the mineral.

To provide some perspective on the potential mineral recovery potential from coal ash, it may be noted that a 2,600 MW power plant typically produces 1.1 million tons of coal ash annually containing silicon oxide, aluminum oxide, iron oxide, and a host of other raw materials [27]. It is reported that by the year 2000 the minerals deficit in the United States will exceed the energy deficit; the trade deficit in minerals may be as high as $100 billion within 25 years [28]. Currently, United States requirements for 22 of the 74 non-energy essential minerals are met principally from foreign sources. Hence, over the long-term, the use of coal ash as a mineral resource may be a possibility. For example, extraction of the aluminum content of the fly ash can completely offset bauxite imports currently [29]. Zinc concentrations in the fly ash are equivalent to zinc concentrations in commercial ores. It appears that continuation of R&D on such uses is essential in the light of a potential mineral crisis in the future.

2.7 R&D Programs - Ash Utilization

Current R&D projects in coal ash utilization are being carried on both in further refinement/understanding of existing uses, and development of new uses.

The manner in which ash is collected can affect its potential for utilization. Ash can be collected either in dry or wet systems. In dry collection systems, fly ash is collected in electrostatic precipitators and stored in large silos. Bottom ash is collected from the boilers in sluice ducts, dewatered, and is stored separately. In wet systems, fly ash and bottom ash are slurried (either separately or in a common pipe) and pumped to holding ponds. Water is recycled from the ponds back into the system when possible.

From a utilization point of view, dry ash or ash slightly wetted (for dust control) is more advantageous in most situations than wet ash. Principal advantages are:

- The ash does not need to be dried for certain uses, saving energy costs.
- If the ash contains CaO and is wet, it may harden upon standing. Dry ash is easier to recover from stockpile.
- Dry ash may be more uniform than wet ash if leaching, agglomeration, and cementation have occurred in the latter.

Currently, the split between wet and dry collection is fairly even [3, 24] although there has been a shift toward dry collection for a variety of reasons.

The U.S. Army Corps of Engineers, the National Bureau of Standards (NBS), the Department of Energy, and the Bureau of Reclamation all are carrying on programs on the influence of coal ash on concrete/cement properties. A particularly active area at present is research in the increased sulfate resistance developed by fly ash concrete. Strength gain, alkali-aggregate reaction, and dimensional stability also are being studied. In addition, numerous small, specific studies are being carried on both by industry and by universities on various fly ash properties in specific situations. The Department of Energy is just completing an evaluation of the use of ash as a cement replacement in concrete. This work focused on the factors affecting increased utilization of ash. DOE is also funding research at Iowa State University on recovery of metal values from fly ash. Programs on development of new uses are being carried on by the TVA and the Coal Research Bureau (CRB) at West Virginia University (WVU). The TVA currently has a pilot scale development program underway using mineral wool technology developed at WVU. Additionally, the TVA, by itself and with outside contractors and sponsors, is looking at extraction of alumina, magnetite, iron, etc. The CRB, in addition to working with TVA on mineral wool, has developed technology for the commercial production of brick from fly ash and bottom ash. The Federal Highway Administration (FHWA) is completing an extensive program on the use of coal ash in road construction. Their results favor use and the Implementation Division is funding projects to demonstrate developed construction technology [12]. The NBS is not currently looking at new areas for ash utilization but anticipates reactivating a currently dormant program in this area [30].

Specific R&D programs in these areas are summarized in Table 2.9 and detailed in the following section. In addition, numerous small R&D projects are being carried on in a variety of organizations.

2.7.1 U.S. Army Corps of Engineers

The Corps of Engineers has been using pozzolans (primarily fly ash) for over 20 years [31]. Generally, 25-35% by weight fly ash is added to concrete (about 45 kg per m^3 or 100 lb/m^3) because it reduces the heat of hydration of the concrete during setting.

Table 2.9

Current Research in Fly Ash Utilization[a]

Primary Sponsor	Contractor	Project Focus/Status	Ref.
U.S. Army Corps of Engineers		Effect of fly ash on properties of concrete. Laboratory work on sulfate resistance, strength, alkali-silicate reaction. Much of the research work has been completed, reports will be prepared within next 1-2 years. (Ongoing)	18
Bureau of Reclamation		Effect of fly ash on properties of concrete. Laboratory work on effect of ash on sulfate resistance. (Ongoing)	23
Coal Research Bureau West Virginia University		Development of new and expanded uses for ash. Laboratory, pilot scale, and demonstration work in a variety of end-uses. Extensive work has been/is being done on a process to produce bricks from fly ahd bottom ash and a process to produce mineral wool from bottom ash. (Ongoing)	32
Dept. of Energy -	Gordian Associates	Overview of use of fly ash for replacement of cement in concrete. Considered supply constraints, economics, technical issues, institutional factors. (Draft Report - December 1978)	33
Dept. of Energy -	Iowa State University	Recovery of metals from fly ash. (ongoing)	5

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[a] Note that this summary specifically excludes research on the use of ash as a soil amendment.

Source: Arthur D. Little, Inc.

Table 2.9 (Continued)

Current Research in Fly Ash Utilization

Primary Sponsor	Contractor	Project Focus/Status	Ref.
Federal Highway Administration		Use of sulfate waste (including FGD sludge) in road construction. Laboratory investigations of lime-fly ash-sulfate waste mixtures for strength-compositional relationship. Engineering investigation of most promising mixtures. (Completed - 1975)	12, 34
		Use of coal ash as a highway construction material. Assessment of available information, some laboratory work. Implementation. Division has sponsored demonstration work. (Most research is complete-published 1976)	7, 12
National Bureau of Standards		Effects of ash on engineering properties of concrete. Laboratory work on sulfate resistance, alkali-aggregate reaction. Sets guidelines for use in specifications by other agency. (Ongoing)	35
		Waste Utilization Program currently inactive. Anticipate reactivation within 1-2 years. (Currently inactive)	30
TVA		Production of mineral wool from boiler slag. Using Coal Research Bureau, W. Va. Univ. process, pilot plant under construction (about 1 tph) will be started up about December 1979. (Ongoing)	36, 37
		Several other smaller projects on alumina extraction, mineral extraction, cenospheres, magnetite. All projects in preliminary economics - technical feasibility - process development phase. (Ongoing)	37

Source: Arthur D. Little, Inc.

The Corps of Engineers reports good results with the material poured to date, but control of fly ash quality is important. They suggest a specification of 6% maximum loss-on-ignition versus the 12% in ASTM specifications; the higher carbon content causes problems with excess air entraining agent to obtain desired air content. Tie-form failures have also occurred due to the slow early strength rise of the fly ash concrete [31].

The Corps of Engineers is currently conducting a multi-faceted program on fly ash and its use in concrete at its Waterways Experiment Station [18]. One area of study is a general analysis of the effect of fly ash on concrete. They are using various kinds of subbituminous and lignite fly ashes blended with Type I and Type II cements; specimens are analyzed for strength. They also have looked at the physical and chemical tests made in acceptance of the cement and ash in these various uses and their appropriateness.

A second area of interest to the Corps is sulfate resistance of concrete. The Corps generally prefers to use Type II* cement in their work because of the lower heat of hydration, the increased sulfate resistance and the increased long-term strength. Type I-P** cement (interblended with fly ash) is being evaluated as a potential substitute for Type II in times of shortages. In this laboratory program, fly ash has been interblended and interground in a Type I-P** cement (22% maximum) and the effects on sulfate resistance are being analyzed. Indications are that the ash increases the sulfate resistance sufficiently to make Type I cement equivalent to Type II* The Corps of Engineers is also reviewing whether the new type of cement manufacturing equipment will significantly change cement characteristics.

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*Type II cement is portland cement for use in general concrete construction exposed to moderate sulfate action or where moderate sulfate action or where moderate heat of hydration is required.

**Type I cement is portland cement for use in general concrete construction. Type I-P is the same as Type I with the addition of a pozzolan.

A third research topic has been the minimization of alkali-silicate reaction. Laboratory work has been done with subbituminous and lignite fly ash, as well as other pozzolans. Test samples were made with high alkali cement and the ability of the ashes to quench or minimize the reaction were measured.

Much of the experimental work in all three of these program areas has been completed. Reports will be prepared within the next year or two [18]. Preliminary conclusions are that fly ash increases sulfate resistance, decreases susceptibility to alkali-aggregate reaction, and increases resistance to sulfate expansion. The Corps also has obtained substantive data on the fly ash cement chemistry and its behavior. Over the next five years, much of the research will be aimed at maintenance and rehabilitation on existing structures. However, some work, on a smaller scale, may continue on alkali-silica reaction and the mechanisms involved.

2.7.2 Bureau of Reclamation

The Bureau of Reclamation uses fly ash extensively as a pozzolan in concrete, primarily in massive structures, dams, canals, etc. Use is predicated on technical reasons; fly ash decreases the heat of hydration in setting cement, fly ash increases the ultimate strength of the cement, and, fly ash is the cheapest pozzolan readily available.

The Bureau has an ongoing research program providing support to fly ash use [23]. The primary focus of this program is currently on the sulfate resistance of fly ash concrete when using "soft" coal ash (i.e., sub-bituminous, lignite). Their laboratory program is concentrating on what causes sulfate resistance in concrete and why some ashes give good resistance and others not. They also have been looking to a lesser degree of heat of hydration reduction by fly ash, and the freeze/thaw durability of fly ash concretes.

2.7.3 CRB-WVU

The Coal Research Bureau of West Virginia University has been studying new and expanded uses for ash. Although many uses have been studied [32, 38, 39] including use as soil amendment, in concrete, and for trace metal recovery, major emphasis has been placed in two areas: a patented process for producing structural materials from fly ash [40, 41, 42, 43, 44] and a process being developed with the TVA for the production of mineral wool from boiler slag (see TVA for discussion).

The process for structural materials was developed to produce high-quality, dry-pressed, fly ash-based brick utilizing most fly ashes; physical and chemical property variations in the fly ash were not found to cause serious problems. Bench-scale studies and pilot plant operations were conducted and process economics were analyzed. A raw materials mix consisting of 72.0% fly ash, 25.2% slag, and 2.8% sodium silicate (as a bonding agent) on a dry basis was used. These brick were much lighter than clay brick and met or surpassed all ASTM standards for clay brick.

In subsequent work, the sand was replaced with bottom ash and slag significantly improving product quality. With improved mixing techniques, a product containing over 97% coal-derived ash has been produced.

A pilot plant was designed and constructed at Morgantown, West Virginia, to produce fly ash-based brick in sufficiently large quantities to permit projection of technical factors and economic data to a commercial scale. Raw materials used were fly ash, bottom ash, and boiler slag obtained from eastern, central, and western coal areas. The work has demonstrated that most, if not all, types of ash produced from American coals can be made into construction products meeting or exceeding ASTM standards for superior-grade face brick.

The pilot plant was designed with a productive capacity of up to 3,000 green (unfired) brick per hour and 1,000 fired brick per day and was successfully operated for several years. It was demonstrated conclusively that the process, with slight modifications, could be applied to virtually any fly ash and that a wide variety of structural products (brick, block, tile, etc.) could be produced. Economics of the process were shown to be highly attractive with a high probability of commercial success. Full-scale design information was developed.

Fly ash brick differ from their clay counterparts in three significant ways:

- Being lighter, they cost less to transport, have and improved market potential for high-rise construction, and are easier for masons to handle.
- Fly ash structural forms are dimensionally precise and are therefore replaceable without change of shape or color.
- Fly ash structural forms can be expanded in size and shape without warpage, size variation or surface defects.

Based upon a detailed economic analysis, the WVU-OCR investigation concluded that fly ash-based brick and other structural materials have significant potential for economic success. This analysis (1973 costs, M&S-345) indicated that total production costs for standard 8-inch facing brick would be $30 to $40 per 1,000 standard brick equivalents [45]. In some cases, costs as low as $24 to $30 per 1,000 may be attainable depending on local market conditions, labor factors, etc. These figures represent total cost FOB the plant including equipment write-off and all overhead costs, such as general and administrative expense.

An attempt to commercialize this process has not been successful to date.

2.7.4 DOE - Gordian Associates

Gordian Associates has completed a study for the Department of Energy looking at the use of fly ash and granulated blast furnace slag as a cement replacement in concrete [33]. This overview study was concerned with supply considerations, availability, cost structure of the market, other economic considerations, technical considerations, and institutional issues. The study concluded that although technical concerns may in many cases be valid (e.g., composition variations, carbon content) they can be handled through proper engineering and still leave a positive cost advantage to the use of ash. Rather, institutional factors have created a bias against the use of ash in concrete and thus hinder its use. If this bias can be corrected through a sufficiently large commercialization program, fly ash use will increase. This report is currently (January 1979) in a draft form and should be released for publication soon.

2.7.5 Federal Highway Administration

The FHWA initiated a comprehensive research program in waste utilization in 1972 and focused on utilization of a variety of wastes in highway construction. Research has been done in two major areas: Category 4C - Use of Waste as Material for Highways; and Category 4D - Remedial Treatment of Soil Materials for Earth Structures and Foundations [46, 47]. Much of this work concerning fly ash and FGD waste has been completed and has been, or is being, reported in the literature.

Results of the major research work on ash utilization are summarized in a report on the use of fly ash in highway construction [7]. The technical information necessary for the use of ash in highway construction has been developed. These uses include:

- Base and sub-base courses,
- Subgrade modifications,
- Embankments,
- Structural backfill, and
- Grouting.

The FHWA has not put a major emphasis in its research program on the use of ash in concrete, although some specific studies have been done in this area [12].

Information has been assembled on production, handling, and physical and chemical properties of fly ash which influences its use in highway applications. The FHWA has considered various factors which affect utilization, case histories, design criteria, testing procedures, and construction procedures. The pozzolanic properties of fly ash make it a good quality base or sub-base course material when used with lime or cement to stabilize aggregates and soils, or when used alone with lime or cement. Strength and durability criteria have been established for this application, and appropriate testing procedures have been developed.

Construction procedures utilize standard equipment and techniques for central mixing or mix in-place operations. Fly ash is used as embankment or structural backfill material over weak or compressible soils because of the reduced surcharge that results from its light unit weight. In addition, it has low compressibility and good stability characteristics, if placed properly. Economies can be realized in the design of retaining structures backfilled with lightweight fly ash. Fly ash improves the flow properties and strength characteristics of grouts. It can be used alone for void-filling or used in conjunction with portland cement, lime, clay, sand, and gravel to develop grouts for applications related to highway structures.

Potential application of FGD waste in road construction has been discussed in a report on sulfate waste use [34]. Mixtures of fly ash, lime, and sulfate waste were evaluated based on fly ash source, form of calcium sulfate, lime type, mixture consistency, curing temperature, admixtures, and impurities. Studies of compound development in selected mixtures were performed. In the second phase of the study, strength-compositional relationships for samples prepared with actual waste sulfates were obtained. Results of this phase were used for the selection of mixtures for engineering evaluation. These mixtures were examined for compressive and tensile strength, freeze/thaw resistance, wet/dry stability, California Bearing Ratio, permeability, and leachability.

While the mixtures were found to have acceptable strength properties, high California Bearing Ratio and low permeability, the durability properties were judged to be marginal. This requires that care and proper precautions be taken in using these mixtures for construction purposes. Laboratory test procedures for mix design and typical specifications which might be used were also suggested.

A third area of research was concerned with use of sulfate waste as a soil conditioner [48, 49]. This work is discussed elsewhere.

2.7.6 National Bureau of Standards

The NBS has been doing research on fly ash for several years. Its resource recovery program has been dormant for several years but is now being revitalized and the Bureau plans to look at new uses for coal ash and FGD waste [30].

Most of the NBS work is aimed at establishing tests which can be referenced by other organizations in establishing standards and specifications for use.

Most of the past and current research has been focused on the effects of bituminous coal ash addition on the durability of concrete [35]. NBS is just beginning work on lignite ashes; current plans are to look at the same areas as have been studied with bituminous. Three specific areas have been looked at and test data are being developed to assess the effect of fly ash on:

- Alkali-aggregate reaction,
- Sulfate attack, and
- Dimensional stability.

Alkali present in the feed materials to cement kilns tends to volatilize and is collected as dust. Cement producers would like to recycle the dust for its lime value. However, as the recycle rate increases, the alkali content of the cement increases. Reaction of alkali present in cement with certain types of aggregate can result in disruptive expansion of the concrete. Fly ash addition tends to quench the reaction. However, current specification for cements to be used with reactive aggregates requires the use of low alkaline cement. If performance specification for blended fly ash-cement could be developed to account for the alkali absorptive capacity of the fly ash, the amount of kiln dust recycled could be increased significantly and higher alkali raw materials could be used.

Concrete is subject to disruptive expansion when exposed to sulfate compounds; sulfates can exist in groundwater, seawater, or other sources. Ash may reduce this susceptibility by quenching the sulfate-cement reaction. However, ash-cement blends are seldom used at present when the concrete may be subject to interaction with sulfates because there are not standard tests for establishing sulfate resistance. The availability of a test which would simulate sulfate attack under field conditions would allow the selection of an appropriate cement (blended or otherwise).

Hydration of MgO and CaO during setting causes concrete to expand. Current ASTM specifications (ASTM C595-74) limit MgO to 5% of the cement clinker. There are indications that the presence of fly ash greatly diminishes the MgO-hydration expansion. Current work is aimed at developing necessary data to support or refute these indications and also to develop more appropriate tests to measure expansion.

The NBS will assist in a potential demonstration project in Mercer County, North Dakota. Several coal-burning power plants are being built in the area, and a plant has been proposed to produce bricks from the fly ash. The NBS will be responsible for developing the necessary standard tests for durability and strength of the bricks. The project is being sponsored by the Mercer County Development Board and is at least two to three years from production.

2.7.7 Tennessee Valley Authority

The TVA is conducting a large-scale feasibility test for the production of mineral wool for insulation from boiler slag [36, 37]. The mineral wool process was developed at the Coal Research Bureau at West Virginia University under a grant from the Bureau of Mines. Tests will be run to determine the financial feasibility of the process at the Thomas Allen Station, Memphis, Tennessee. The TVA prototype will be semi-commercial size and use four tons per hour of slag on a single eight-hour shift. The slag is from a single 300-MW unit, with a wet bottom collection system. Slag will be ejected from the boiler at about 1100°C (2000°F), limestone is added as flux and the temperature will be raised to 1370°-1540°C (2500°-2800°F); the fibers are spun conventionally. The process is only applicable to wet bottom units. TVA currently is working on the design for the unit and expects to have the unit operational by late 1979 [37]. They have run the process in a cupola-type unit. Limestone is added to drop the slag viscosity. Preliminary estimates are that the process has an approximate payout period of five years.

The TVA staff is currently working in conjunction with an aluminum company to determine the economic feasibility of extracting alumina from boiler fly ash. Preliminary economics indicate that extracting alumina from fly ash might well be competitive with conventional technologies for the extraction of alumina from Georgia clay (kaolin clay). The TVA is presently considering a 2 ton/hour pilot plant facility to investigate the feasibility of extracting and recovering certain minerals (alumina, iron, etc.) from boiler fly ash.

TVA is also working in conjunction with some commercial interests based in St. Paul, Minnesota, on the development of a process for extracting magnetite from boiler fly ash. Magnetite is a major constituent of the heavy medium slurry used in coal cleaning plants, and TVA believes that the fly ash produced at its 1,700-MW Kingston plant contains sufficient magnetite to feed the TVA Paradise coal cleaning plant.

A TVA program currently is underway by the TVA to study the possibility of using fluidized bed combustion wastes as soil additives to stabilize load-bearing fill/sub-base for small airport runways, highways, etc.

One other project in progress, being done with P&W Industries, involves determining the feasibility of separating and collecting cenospheres (hollow glass balls) from dry fly ash and marketing them commercially for application as fillers for plastics, paint extenders, etc.

2.7.8 GM - Plastic Filler

The Polymers Department of General Motors Research Laboratories has been studying the use of fly ash as a filler in polypropylene [72, 73]. Mineral fillers currently used in plastics consist largely of silica, alumina, and other oxides in the form of kaolin or talc.

GM obtained fly ash from several sources and in a laboratory program characterized the particle size, density, and chemical composition. Samples of filled polypropylene were prepared with appropriate antioxidants on a roll mill at 190°C (400°F) and by extrusion at 205°C (425°F). The material was granulated for use in injection molding.

Results indicated that fly ash particle size was important in some applications. Smaller particles tend to give products with greater impact strength and better elongation properties than do larger particles.

However, particle size apparently had no measurable effect on yield strength or modulus. Tensile strengths were reported to be 2.07 to 2.48×10^7 Pa (3000 to 3600 psi) and tensile moduli were 2.07×10^7 to 2.76×10^9 Pa (300,000 to 400,000 psi) for the filled plastics.

GM postulates that the fly ash-filled material is low in strength and stiffness because of the particle shape -- irregular and jagged versus platelike talc. The higher length/thickness ratio of talc provides more reinforcement to the polypropylene matrix.

2.7.9 Other R&D

Some limited information is available on the following:

- The Fossil Energy Division of DOE has funded research at Iowa State University on the recovery of metals from fly ash. The objective of the program is to investigate the chlorination of coal fly ash as a method for recovering the aluminum and to develop a process for the large-scale recovery of aluminum and iron from fly ash by this method. Previous work here has achieved 80% recovery of aluminum as aluminum trichloride (Al_2Cl_6).
- The Federal Energy Administration has funded research at Southwest Research Institute for the evaluation of utilization of slag, fly ash and kiln dust as additions to portland cement by intergrinding with clinker or blending. Fly ash was added at 0-15% and blends were tested at ages up to one year for physical and other characteristics.
- The American Electric Power Service Corp. is funding a field study of fly ash construction at West Virginia University. The aim of the research is to study the field behavior of fly ash embankments and stabilized fly ash base courses to provide engineering design data. Laboratory and field studies included (1) placement and compaction techniques; (2) properties of the in-place material as a function of time and location in the embankment and/or base; (3) effects of frost action on material

properties; (4) moisture retention by fly ash and its effect on strength; (5) effects of traffic on material properties; (6) corrosion of metals embedded in fly ash: (7) permeability of fly ash; and (8) immediate and long-term compressibility of fly ash.

3.0 UTILIZATION OF FGD WASTES AND BYPRODUCTS

3.1 Introduction

FGD systems are generally categorized into two groups:

- Nonrecovery--or throwaway--systems, which produce a solid or liquid waste with little market value, and
- Recovery systems, which produce primarily purified, concentrated SO_2 elemental sulfur or sulfuric acid as a byproduct for sale.

At present, the overwhelming majority of FGD systems for controlling emissions from utility and industrial boilers utilize some form of nonrecovery technology. Over 90% of the more than 50,000 MW of utility boiler capacity now committed to flue gas desulfurization involve nonrecovery processes. This dominance of nonrecovery systems is expected to continue for the near future. Except in site-specific cases with favorable local market conditions for the by-products (sulfur or sulfuric acid), recovery processes are more expensive.

The technology of recovery and nonrecovery systems, the characteristics of the wastes produced, and projection of waste generation are discussed in Volume 3. This chapter provides a review of waste utilization, both current practices and potential utilization alternatives that have been or are being investigated. Emphasis is placed upon wastes from nonrecovery processes, since nonrecovery technology will be the principal approach to the desulfurization of flue gases from fossil fuel combustion, at least over the next 10 to 15 years. Furthermore, the primary byproduct of recovery systems will be sulfur or sulfuric acid, conventional products for which markets are already established.

3.2 Utilization of Nonrecovery FGD Wastes

3.2.1 Description of Wastes

Commercially available nonrecovery processes can be conveniently subdivided into two groups according to the form of the waste material produced--those which convert the SO_2 into a solid waste and those which produce a liquid waste. Nonrecovery systems can also be classified according to the manner in which the flue gas is contacted with the SO_2 sorbent--i.e., wet scrubbing processes versus dry processes.

All nonrecovery systems now in commercial operation on utility and industrial boilers are wet processes involving contact of the gases with aqueous slurries or solutions of absorbents. Although most nonrecovery wet systems can withstand relatively high levels of particulate and trace contaminants and many in the past have been designed for simultaneous SO_2 and particulate control, most wet systems being installed today on utility boilers are downstream from high efficiency electrostatic precipitators in order to ensure more reliable service. The notable exceptions are systems designed to utilize alkalinity in the fly ash for all or part of the SO_2 removal. These frequently incorporate simultaneous fly ash and SO_2 control.

Dry non-recovery processes have not yet been commercially demonstrated on a utility scale in the United States. However, a number of different approaches have been investigated, including dry injection of sorbents into the boiler and flue gas and the use of spray dryers. All of these involve simultaneous SO_2 and particulate control, and all produce a dry waste material. The most promising approach at present employs spray dryers for contacting the flue gas with slurries (or solutions) of calcium hydroxide or sodium carbonate/bicarbonate. Three such systems have been contracted for application to utility-scale boilers.

3.2.1.1 Solid Wastes

The four basic types of nonrecovery systems producing solid wastes are:

- Direct lime scrubbing,
- Direct limestone scrubbing,
- Alkaline fly ash scrubbing, and
- Double (dual) alkali.

The first three of these utilize slurries of lime, limestone, or ash to contact the flue gases and produce slurries containing 5-20 wt% solids which are either discharged directly or partially dewatered and possibly further processed prior to discharge. All three of these are commercially demonstrated technologies. The fourth, the double alkali process, is a second generation technology which has been applied successfully to industrial-scale boilers but is only now reaching commercial demonstration on utility boilers. Double alkali processes utilize solutions of sodium salts for SO_2 removal which are then regenerated using lime to produce a waste solid that is discharged as a filter cake.

In addition, dry sorbent based FGD systems are also likely to be in commercial use by the early 1980's. These will be based on lime, sodium salts or other sorbents and will produce dry solid wastes. To date, the extent of focus on utilization of such dry sorbent wastes has been minimal. EPA is planning some pilot studies on dry sorbent processes and dry surbent wastes in 1979 [50].

The quantity and composition of ash-free FGD wastes are dependent upon a number of factors including: coal characteristics (most importantly, its sulfur content and heating value); SO_2 emission regulations; the type of boiler and its operating conditions; and the type of FGD system and its operating conditions. In general, the quantity of dry, ash-free FGD waste produced varies from about 2.0 to about 3.5 times the quantity of SO_2 removed from the flue gas. Hence, a typical utility boiler operating at a 70% load factor could produce anywhere from 50 to 500 tons of dry, ash-free solids annually per megawatt of boiler capacity.

The principal substances making up the solid phase of FGD wastes are calcium-sulfur salts (calcium sulfite and/or calcium sulfate) along with varying amounts of calcium carbonate, unreacted lime, inerts and/or fly ash. In wet processes the ratio of calcium sulfite to calcium sulfate is a key design and operating parameter, especially for direct scrubbing systems since it can affect not only the scale potential of the system but also the waste solids properties. The relative amounts of calcium sulfite and sulfate present depend principally upon the extent to which oxidation occurs within the system. Oxidation is generally highest in systems installed on boilers burning low sulfur coal or in systems where oxidation is intentionally promoted. In most medium to high sulfur coal applications, oxidation of sulfite to sulfate in the scrubber system amounts to only 10-30%, and calcium sulfite is the predominant material in the waste. When the sulfate content of the waste solids is low, calcium sulfate can exist with calcium sulfite as a solid solution of the hemihydrate crystals ($CaSO \cdot 1/2H_2O$). At higher calcium sulfate levels, gypsum ($CaSO_4 \cdot 2H_2O$) becomes the predominant form of calcium sulfate. At very high levels of oxidation (greater than 90% oxidation of the SO_2 removed) all of the calcium sulfate usually will be present as gypsum.

Because the differences in the crystalline morphology of hemihydrate and dihydrate solids not only reflect the chemical composition but also can affect the physical and engineering properties, it is convenient to classify FGC wastes on the basis of the ratio of calcium sulfate to total calcium-sulfur salts. The three categories are as follows:

- Sulfate rich ($CaSO_4/CaSO_x \geq 0.90$),
- Mixed ($0.25 < CaSO_4/CaSO_x < 0.90$), and
- Sulfite rich ($CaSO_4/CaSO_x \leq 0.25$),

where $CaSO_x$ is the total calcium-sulfur salts.

Calcium sulfite wastes present a problem because of difficulty in dewatering. However, calcium sulfite wastes can be oxidized to calcium sulfate, either intentionally in the scrubber or in an external oxidation reactor. From the viewpoint of utilization, calcium sulfate is the desirable FGD by-product.

EPA studies at the Industrial Environmental Research Laboratory (Research Triangle Park, North Carolina) have shown that calcium sulfite can be readily oxidized to gypsum by simple air/slurry contact in the hold tank of the scrubber recirculation loop. Although the rate of oxidation reaches a maximum at a pH of 4.5 and then declines at higher pH, it was found that oxidation could be accomplished at a practical rate up to a pH of about 6.0 [69].

In Japan, where natural gypsum is not available, forced oxidation in scrubber systems has been employed extensively to produce a high-quality gypsum raw material for the cement and wallboard industries. Japanese FGD units are primarily used on oil-fired boilers and do not have to contend with fly ash admixtures with gypsum. In the United States, FGD systems are mainly on coal-fired boilers and usually supplement fly ash collection units; gypsum admixture with fly ash is possible in poorly designed or operated systems. Furthermore, scrubber gypsum may be unable to compete extensively with the widely available natural gypsum except in some specific areas. Thus, the incentive in the United States has been to develop simplified forced oxidation procedures and has been directed only toward improving waste solids handling and disposal properties and not towards the production of gypsum with minimum fly ash content; moreover, the oxidation reaction need be carried only to about 95% completion if one is only aiming towards relatively good dewatering characteristics.

There is little information currently available on the composition of wastes from dry scrubbing systems utilizing spray dryers. However, while all of these wastes would contain fly ash, the fraction of the waste resulting from SO_2 control would be expected to be similar in chemical composition to those produced by wet processes using the same sorbents. For lime-based dry scrubbing, the FGD wastes should consist primarily of a mixture of calcium sulfite, sulfate, and unreacted lime. The quantity of unreacted lime, however, may be somewhat higher than in wet scrubbing wastes owing to the higher stoichiometries that would probably be required. The mix of calcium sulfate and sulfite solids may also be somewhat different, both in terms of their relative quantities as well as the crystalline forms present.

For dry systems utilizing alkaline sodium salts (e.g., nahcolite or sodium bicarbonate) the waste solids would be expected to contain in addition to fly ash a mixture of principally sodium sulfate, sulfite, chloride, and unreacted carbonate. These would be similar in composition to the wastes produced from once-through sodium solution scrubbing except that the solids would be discharged as a dry material rather than as a liquid.

3.2.1.2 Liquid Wastes

There are two different liquid waste-producing FGD processes that are in commercial operation on combustion boilers--(1) once-through-scrubbing using solutions of alkaline sodium salts and (2) scrubbing using ammonia-laden water. Of the two, once-through sodium scrubbing has achieved the widest acceptance, having been applied to many industrial steam plants and a few utility boilers. Once-through sodium scrubbing produces a waste liquor containing primarily sodium sulfate, sulfite, and chloride at total dissolved solids concentrations generally in the range of 15-30 wt%.

Most of these waste liquors also contain significant levels since the systems are used for combined particulate and SO_2 control. Frequently, the waste liquors are air-sparged to oxidize any residual sulfite to sulfate, especially where wastes are discharged for disposal.

3.2.2 Current Utilization Practices

The available data on industrial and utility boiler FGD systems indicate that there is very little commercial utilization of FGD wastes in the United States. In fact, the only commercial utilization reported for nonrecovery wastes is the reuse of once-through sodium scrubbing liquors at pulp and paper plants [51]. There are two such plants where the scrubber discharge liquor is recycled for use in pulping operations.

3.2.3 Potential Utilization Alternatives

A variety of potential uses for stabilized and unstabilized calcium sulfite/sulfate wastes from lime- and limestone-based scrubbing have been proposed including:

- Road construction base,
- Cement and concrete manufacture,
- Filler in glass,
- Fertilizer and fertilizer base,
- Fill material (structural or landfill),
- Brick manufacture,
- Commercial gypsum substitute (in wallboard and cement) either as a direct waste or converted sulfite-rich material,
- Aggregate,
- Recovery/reuse of chemical values (including beneficiation), and
- Artificial reef constructions (although this is generally considered to be disposal and is discussed in Volume 5).

Recent studies [7, 43] have indicated the feasibility for use as structural fill, brick manufacture, and highway construction, although the current level of development is low at this time. The technical feasibility of most of these product uses has been evaluated on only a limited scale; and even for those which have been shown to be technically feasible, the economic viability is still uncertain. Also, for some of the potential uses that have been proposed, coal ash can also be used (as mentioned earlier), and in many cases, coal ash will be the preferred material.

A brief discussion of some of the more viable options is presented below prior to the discussion of research and development programs in waste utilization.

3.2.3.1 Structural Landfill

Unstabilized FGD waste typically has poor structural properties. Sulfite-rich materials are usually difficult to dewater and can be structurally unstable (tendency to liquefy and flow). As a result, unstabilized waste probably will not be useful for fill.

Stabilized waste may provide viable fill materials. On a demonstration basis, stabilized FGD waste has been used for road base, road fill, lightweight aggregate, and artificial reefs [52]. Its use also has been suggested for mine reclamation, subsidence control, acid mine drainage control, etc. [11]. The stabilization processes are discussed in more detail in Volume 3.

As more FGD systems begin to utilize stabilization procedures with landfill of wastes, the modified and stabilized waste might find an outlet for use in structural fills and enbankments. The stabilized waste usually contains significant amounts of fly ash as a result of the stabilization process. The structural properties of stabilized waste may make it advantageous for landfill or strip mine reclamation.

3.2.3.2 Gypsum

Forced oxidation of FGD waste can yield gypsum as an end-product. Gypsum so produced may be useful for wallboard manufacture, cement production (as a set retarder), and as a soil additive; wallboard has the potential for being the largest end-use market.

The technical differences between by-product gypsum and natural gypsum are somewhat uncertain, and conflicting information exists. By-product gypsum has a smaller particle size and contains more free moisture (20% versus 3% in natural) than natural gypsum. It is up to 96% pure calcium sulfate, with the primary impurity calcium carbonate and less than .05% solubles [67]. Some by-product gypsum is purer than natural gypsum; in one test, Chiyoda process gypsum was about 90% calcium sulfate versus 80% purity for natural gypsum being imported from Canada [69].

Industry (wallboard) manufacturers have expressed concern over the possible effect of contaminants (e.g., fly ash, reagents, calcium sulfite, and soluble salts) on product quality and economics, and the effect of variations in sludge (gypsum) quality and composition on product quantity and economics [35]. Wallboard or cement gypsum can contain up to 15% $CaCO_3$, with the nominal grade containing 8-15% $CaCO_3$. Sulfuric acid may be added to convert excess $CaCO_3$ to gypsym and also to lower the pH to enhance oxidation of sulfite to gypsum. The effect of entrained trace metals and elements on gypsum is unknown.

Wallboard is currently produced from natural gypsum which is either mined domestically or imported. Production is generally from a captive source, as the industry is vertically integrated and most companies own or control their own mines either here or abroad. This could make market entry for by-product gypsum very difficult. The degree and amount of impurities that can be tolerated in gypsum depend upon intended use. In wallboard manufacture, impurities in gypsum reduce the strength of the product and more pounds of gypsum are required to achieve a given strength of finished wallboard.

Entrained coal fly ash apparently has little effect on the quality of the wallboard produced, although it does produce a dark-colored gypsum which may have some associated sales resistance [35]. Chloride, which occurs at higher concentrations in scrubbers on coal-fired versus oil-fired utilities, may cause corrosion problems in wallboard installations [52]. Chloride also affects calcining temperature, set time, and stucco slurry consistency. Soluble chlorides are usually limited to 0.02% to 0.03% if the gypsum is used in wallboard. The hydrous sulfate salts affect moisture pickup and bonding characteristics of the wallboard and are also limited to 0.02% to 0.03%. Hydrous clays of up to 1.0% to 2.0% may be tolerated [54]. Gypsum is also used as a soil conditioner; this use is discussed later in this section.

In Japan, by-product gypsum is widely produced, as most utilities equipped with lime/limestone scrubbing convert the sludge produced to gypsum through intentional forced oxidation. However, a distinct set of circumstances exists which tend to encourage this practice:

- Regulatory agencies frown on throwaway or unoxidized waste.
- There is a scarcity of suitable land for waste disposal.
- Since there are no natural sources of gypsum, market demand is high.
- Boilers are generally oil fired rather than coal fired.

Japan has little or no natural gypsum and, therefore, must depend on imports and byproduct gypsum from chemical processes (e.g., production of phosphoric acid). When lime/limestone scrubbing was introduced, this ready market for gypsum led most system suppliers to develop oxidation units. Most Japanese power plants burn oil; the ratio of power produced from oil to that from coal is about 10 to 1 [70]. The gypsum from scrubbing coal-fired boilers may be less acceptable becasue of the higher impurity content from entrained fly ash, chlorides, etc. [52, 70].

Most of the FGD gypsum made in Japan goes to the wallboard industry where it commands a higher price than in the cement industry where higher fly ash content can be tolerated. The market for FGD gypsum in Japan has held up well, considering the large amounts being produced as a scrubbing byproduct and as a byproduct of phosphoric acid manufacture. However, recently supply has exceeded demand, and this may affect the overall situation.

The potential for utilization of gypsum in the United States is probably not as favorable as that in Japan. The United States has more open land available for sludge disposal and hence, disposal costs are less than in Japan. Moreover, natural gypsum sources are available to satisfy the market at reasonable cost. Furthermore, FGD systems in the United States are and will continue to be installed on coal-fired boilers; potential admixture with coal ash would impact quality control requirements. Market studies by the TVA and others [55,56,67] indicate that the production and marketing of abatement gypsum may offer substantial economic advantages over FGD waste disposal but that abatement gypsum probably cannot compete with natural gypsum except in specific situations. (See Section 2.3.) Successful entry of abatement gypsum into the wallboard industry as a replacement and competitor of naturally mined gypsum seems uncertain. The wallboard industry is proceeding with caution in accepting abatement gypsum as a substitute despite some advantageous properties of abatement gypsum and several successful demonstrations.

Gypsum could be utilized also in the manufacture of portland cement [67]. This is practiced in Japan and does not require as high a grade of gypsum as wallboard manufacture. However, little information exists on the technical requirements for gypsum in this application. This market segment is not generally integrated into natural gypsum production and marketing so that market penetration may be easier here than in the wallboard industry. Gypsum is used in the cement industry as a set retarder; it is added to clinker and ground into the final product. The sulfite content of the by-product gypsum may limit its use. In general, the specifications for use in cement are not as stringent as those for use in wallboard.

The use of by-product gypsum in agriculture, although representing a smaller market than either of the above uses, looks promising. At least one source indicates current commercial utilization in this capacity [67]. The use of by-product gypsum is discussed more fully in Section 3.2.3.4.

3.2.3.3 Aggregate

Production of aggregate from FGD waste is a potential large volume market because of increasingly more expensive naturally occurring aggregate.

A mineral aggregate containing sludge was developed by I.U. Conversion Systems and has been satisfactorily used in a demonstration project [57]. Mineral aggregate also has been produced using an autoclave process where pelletized sludge is hydrothermally agglomerated by curing with saturated steam at 300 psi. This process would be faster than that proposed by the Corson Company but more expensive because of the energy requirements.

Manufacture of lightweight aggregate has also been proposed as a potential use for FGD wastes. Lightweight aggregate currently is produced by expanding shale, slate, or clay. The growth in use of lightweight aggregates (a doubling of use is expected in the next 20 years) and the shortages expected to occur in certain urban areas are likely to favor such potential utilization of FGD wastes. A number of plants have been constructed that sinter fly ash into a lightweight aggregate and in some areas this sintered fly ash has been found to be economically competitive [58]. Fusion tests indicate that control of the process with FGD waste might be difficult because of the variability of the sludge and the narrow softening - fusion temperature band.

Mineral aggregate shows considerable promise for large volume utilization of by-product sludge, but technical and economic problems must be solved before this use is commercialized.

3.2.3.4 Agricultural Uses

FGD scrubber waste may be useful as a soil amendment, a gypsum substitute, or in fertilizer. Such use will be possible in some areas, for example, California and the southeastern states [52], but will probably be limited to local markets which may coincidentally be available to a utility.

Research efforts directed toward the use of FGD waste as a fertilizer base or additive range from simple studies of the effects of directly adding unstabilized waste to soil to more sophisticated conversion process technologies related to fertilizer production.

As a direct soil additive, FGD waste has potential benefits including its neutralization capability and its use as a source of sulfur, calcium, magnesium, and certain necessary trace metals that may participate in plant growth. However, FGD waste has little or no nitrogen, phosphorous, or potassium value, and the presence of high levels of TDS (particularly sodium and chlorides) as well as some potentially toxic trace metals may present problems in agricultural uses in any large quantities.

Oxidized FGD waste may be useful as a gypsum substitute. Gypsum is used in the following ways:

- As a soil amendment on high-alkali soils,
- As a neutral source of calcium, and
- To provide sulfur on sulfur-deficient soils.

Soil amendments may be of three types: soluble calcium salts (calcium chloride and gypsum); low solubility calcium salts (limestone); and acid or acid-forming compounds such as sulfur, sulfuric acid, iron, and aluminum sulfate [5]. Because of their low cost and suitability, gypsum and sulfur are the most widely used.

Peanuts require large amounts of soluble calcium in the soil surface to facilitate pegging and nut formation. Gypsum use is recommended when soil pH is already satisfactory but additional calcium is needed (gypsum is a non-alkaline source of calcium).

Where soils are deficient in sulfur, gypsum can be used as a source of this nutrient. However, since the requirement per acre is usually small (∿10 lb/acre), it is usually easier to simply add the sulfur to fertilizer and apply both in a single application.

A process to produce granular fertilizer from scrubber waste has been proposed in the literature and currently is being developed [59]. Research is being conducted by the TVA as part of an Interagency Agreement involving the use of lime/limestone scrubbing wastes in agricultural applications. This portion of the work involves use of direct lime and limestone scrubbing system wastes as a filler material in and as a source of sulfur for fertilizer. The work includes pilot testing of the fertilizer inclusion/production process, testing of field plots using wastes/fertilizer mixtures, and studies of the costs associated with producing such a fertilizer and its market potential. To date, initial pilot plant tests have shown some problems in introducing waste into standard fertilizer production units. (See Section 2.3, R&D - TVA.) Waste also may be useful for its liming value [59]. The liming value will probably vary with the unreacted lime and the amount and basicity of the fly ash contained in the waste. Gypsum and sulfite have little or no liming value but provide soluble calcium and sulfur. Fixation additives may affect the value of sludge as fertilizer. Little information is available on this end-use, and it probably would be economical within a limited distance from the waste source.

3.2.3.5 Building Brick

Brick production by the conventional sintering process as used for fly ash or clay brick is not technically feasible for FGD waste raw materials at this time. SO_2 is evolved during the sintering process, and control of the level of softening during sintering is difficult (see lightweight aggregate). Calcium silicate brick has been made from FGD waste [38]. The brick is a mixture of scrubber waste, silica sand, and lime, which is pressed into shape and then autoclaved. The bricks are of good quality and meet the ASTM specification for calcium-silicate brick [38]. Calcium silicate brick is not a common building material in the United States, and major market changes would have to take place before this method of utilization would become practical.

3.2.3.6 Recovery of Chemicals

Various investigators have suggested and explored the concept of the recovery of useful chemicals from scrubber wastes (FGD or FGC). Furthermore, recovery FGD systems produce sulfur or sulfuric acid as by-products. At present, two [2] utility plants employ recovery FGD systems. Thus, the list of possible by-product chemicals from scrubbing the sulfur contained in flue gases includes calcium oxide, magnesium oxide, elemental sulfur, sulfuric acid, sodium sulfate, sodium sulfite, and ammonium sulfate. Some of these chemicals can be obtained from scrubbers using recovery systems but may not be practicably obtainable from lime/limestone sludge because of the extensive reprocessing necessary to extract these materials. The one potential exception is production of elemental sulfur. A variety of processes have been suggested for the production of elemental sulfur from FGD waste [56, 60, 61]. None of these processes have been implemented on a full-scale basis.

3.2.4 R&D Programs - Nonrecovery FGD Wastes

The largest ongoing research program on FGD waste utilization is that sponsored by the EPA. The EPA is currently sponsoring four projects connected with utilization of nonrecovery FGD wastes:

1. Converting FGD waste to sulfur (Pullman-Kellogg),
2. Converting FGD waste to fertilizer (TVA),

3. Utilizing FGD waste to extract alumina from kaolin clay (TRW), and
4. Marketing of FGD waste as gypsum (TVA).

A fifth project has been discussed on utilization of FGD waste in cement manufacture, but no projects are reported. The overall objectives of the projects are shown in Table 3.1. The current status is as follows:

- The Pullman-Kellogg sulfur project has proceeded through pilot plant testing of the critical process units. Evaluation of process economics is necessary before further work proceeds.
- Fertilizer production from waste, being studied by TVA, is currently on hold, partly because of uncertainties over regulatory requirements in the future. A pilot plant program has been developed, but further work is unlikely until resolution of these requirements [37].
- The TRW study of alumina production with FGD has been completed and a final report published. This economic study concluded that FGD waste utilization for alumina production from kaolin clays, coupled with an adjacent cement plant to utilize by-product dicalcium silicate, may be feasible in the future depending on alumina prices. A future series of laboratory projects is suggested in the report.
- The TVA has recently completed a study of by-product marketing of sulfuric acid, sulfur, and gypsum [67]. A linear programming model was used to determine the potential marketability (based on low-cost constraints) of the three by-product wastes. This study is discussed in more detail in Section 3.4.

Northern States Power Corporation and Texas A&M University have an ongoing program to demonstrate the technical feasibility of lightweight aggregate production from FGD waste and clay. Bench-scale work has been

Table 3.1

Current Research in FGD Waste Utilization

Primary Sponsor	Contractor	Project Focus/Status	Ref.
Environmental Protection Agency	Pullman-Kellogg	Demonstration of process for conversion of FGC scrubbing waste to sulfur and calcium carbonate. Pilot plant work demonstrating technical feasibility of major units has been completed. Economics need to be evaluated before further scale-up. (Ongoing)	60, 61
	TVA	Assessment of FGC waste for conversion fertilizer. Some pilot plant work has been completed. Project is currently on hold awaiting decision vis-a-vis RCRA regulations. (On Hold)	60, 61
	TVA	Marketing of byproducts from FGC waste. Marketability study of byproduct sulfur, sulfuric acid, and gypsum using least-cost linear programming mode. The study has been completed and reported. (Completed Final Report, October 1978)	60, 61
	TRW	Process design and economic evaluation of proposed process to use FGC waste was for the extraction of alumina from kaolin clay with calcium disilicate byproduct recovery. (Draft Report)	60, 61
Northern States Power	Texas A&M University	Assessment of use of FGD waste for production of lightweight aggregate. Bench scale work completed. Pilot scale work under development.	62

Source: Arthur D. Little, Inc.

completed, and work is proceeding on a pilot level. These projects are discussed in detail in the following section.

In addition to these programs, several other R&D projects are ongoing:

a. Southern Services has contracted with the U.S. Gypsum Company for test runs of wallboard production utilizing abatement gypsum generated from the Chiyoda Thoroughbred 101 dilute acid scrubber at the coal-fired Scholz Plant of Gulf Power. These production runs were conducted in June and December 1976. The full results of these tests are not yet available, but indications are that the tests were reasonably successful [69].

b. Southern California Edison (SCE) has been experimenting with gypsum production from its Highgrove Station Unit No. 4. This is a 10-MW oil-fired facility. A 50-ton full-scale wallboard production run has been completed, but test results were not available.

c. The Purity Corporation is pursuing the development of a patented process for using waste as a fertilizer. The process makes use of the sulfur and calcium in the wastes with the addition of phosphorous and ammonia to produce a granulated fertilizer.

d. The University of Florida Agricultural Research Center in Quincy, Florida, is testing for the Southern Company the use of two different wastes as soil amendments. The two wastes being tested are the dual alkali filter cake and gypsum from the ADL/CEA and Chiyoda prototype systems, respectively, at the Scholz Steam Plant in Sneads, Florida. Testing is directed toward determining the effects of different concentrations of the wastes on soil pH and the availability of calcium, magnesium, potassium, and phosphorous. Tests are also being conducted to project the effects of these wastes on the dry matter yield of soybeans and peanuts.

3.2.4.1 Pullman Kellogg [61,63]

The M. W. Kellogg Company developed the "KEL-S" process for conversion of lime/limestone scrubbing wastes to elemental sulfur with recovery of calcium in the waste as calcium carbonate.

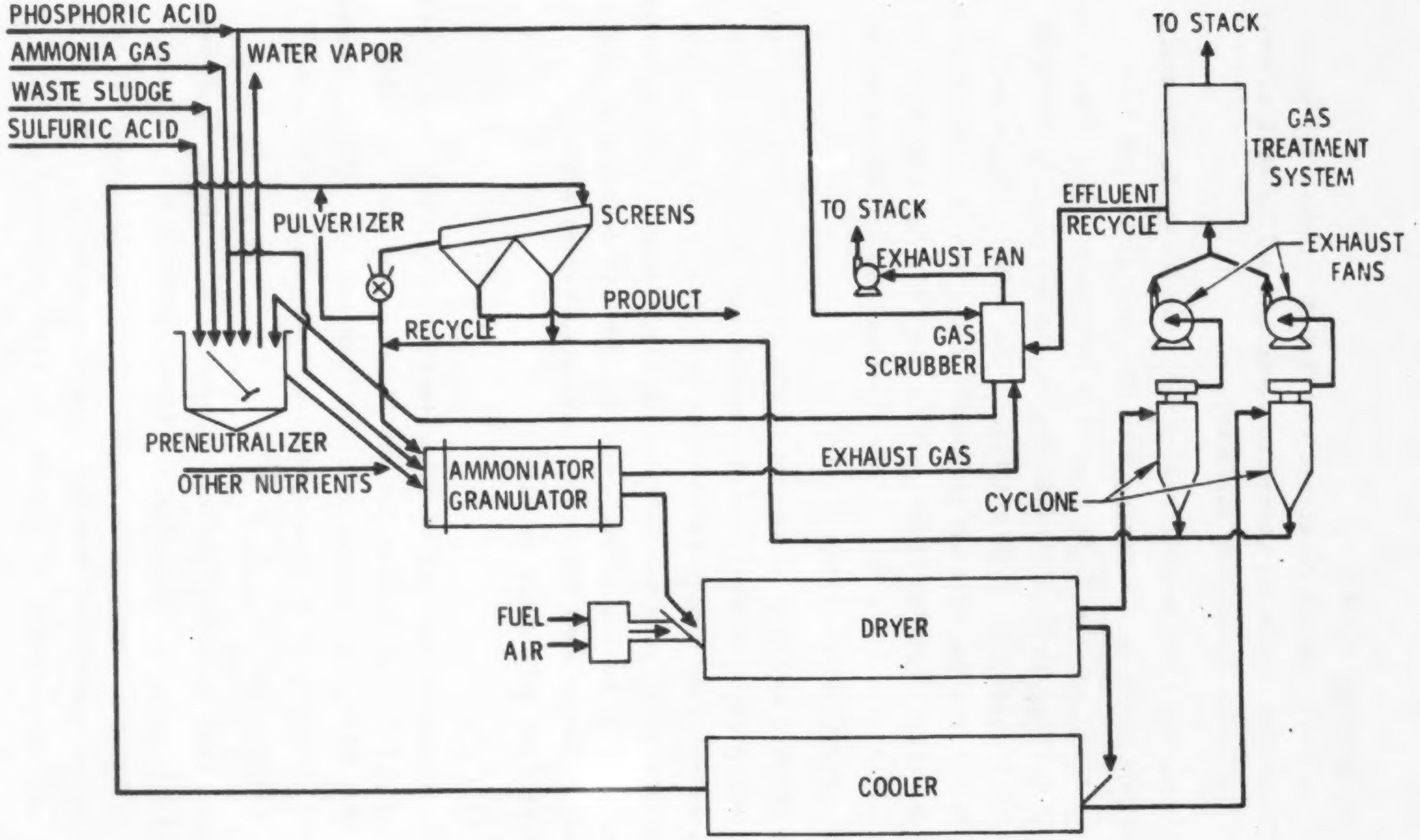
As conceived, the process will reduce $CaSO_3$ and $CaSO_4$ in FGD waste to calcium sulfide (CaS) in a rotating kiln with coal. The CaS is reacted with hydrogen sulfide (H_2S) producing calcium hydrosulfide, i.e., ($Ca(HS)_2$). The $Ca(HS)_2$ is dissolved in water; the solution is filtered and reacted with CO_2-rich gas from the kiln. The $Ca(HS)_2$ reacts with the CO_2 to form H_2S gas and calcium carbonate ($CaCO_3$) which precipitates. Some of the H_2S is recycled for reaction with the CaS; the remainder is converted to sulfur in a Claus unit. The precipitated calcium carbonate is recycled to the scrubber system.

Pilot-scale work has been conducted to evaluate the technical feasibility of various process steps. The production step (reduction to CaS and dissolution) has been demonstrated to be technically feasible, and the calcium regeneration step has been proven satisfactory. The economics of the process need to be evaluated before any further decision on the process is made. Design data need to be generated before scaleup to a larger prototype test unit could be made.

3.2.4.2 TVA [61, 63]

The TVA is assessing the use of lime/limestone FGD waste as a filler material in and a source of sulfur for fertilizer. The work is being performed by TVA, Office of Agricultural and Chemical Development, Muscle Shoals, Alabama, as part of an interagency agreement on the evaluation of FGD waste utilization.

The process (see Figure 3.1) mixes phosphoric acid (H_3PO_4) and ammonia with dewatered FGD waste at approximately 93°C (200°F) in a preneutralizer. The hot mixture is transferred to an ammoniator-granulator where the slurry solidifies as it is ammoniated, forming a granular material. This material is dried, cooled, and screened to obtain a fertilizer product.


PHOSPHORIC ACID
AMMONIA GAS
WASTE SLUDGE
SULFURIC ACID
WATER VAPOR
PULVERIZER
SCREENS
PRODUCT
RECYCLE
PRENEUTRALIZER
OTHER NUTRIENTS
AMMONIATOR GRANULATOR
FUEL
AIR
DRYER
COOLER
TO STACK
EXHAUST FAN
GAS SCRUBBER
EXHAUST GAS
EFFLUENT
RECYCLE
TO STACK
GAS TREATMENT SYSTEM
EXHAUST FANS
CYCLONE

Source: [61]

Figure 3.1 Process Flowsheet for Producing Solid Granular Fertilizer Material from Scrubber Waste

The tests used waste produced at the 1-MW limestone pilot unit located at the TVA Colbert Steam Plant. Severe foaming occurred during the introduction of waste, phosphoric acid, and ammonia into the preneutralizer. A specially designed preneutralizer was constructed to eliminate the problems encountered. Alternative methods and locations for adding the waste, acid, and ammonia, improved agitation, foam breaking methods, and insulation were tested. Initial testing with the modified preneutralizer resulted in sulfur losses ranging from 78 to 90 wt% and an ammonia loss of 34 to 61 wt% based on input quantities.

The losses are suspected to result from a reaction between calcium sulfite in the waste and phosphoric acid:

$$3CaSO_3 + 2H_3PO_4 \rightarrow Ca_3(PO_4)_2 + 3H_2SO_3$$
$$H_2SO_3 + 2NH_3 \rightarrow (NH_4)_2SO_3$$

Laboratory tests and past pilot plant experience indicate that these reactions are possible.

It is expected that these unwanted reactions can be prevented by either neutralizing the phosphoric acid before it comes into contact with the waste or by oxidizing the calcium sulfite to calcium sulfate before feeding to the preneutralizer. Therefore, tests are being planned to determine the feasibility of using oxidized sludge in the preneutralizer.

Additional tests were conducted to define preneutralizer operating conditions. These included the effect on ammonia-to-phosphoric acid ratios and the location of the waste feed and its flow rate. Problems, including release of SO_2, sparger plugging, and temperature and fluidity control, were encountered under the conditions tested. Indications are that pH may control the fluidity and SO_2 release problem.

Plans and cost estimates for pilot plant development of a cross-pipe reactor to possibly overcome these problems have been developed. This program is currently on hold. A key factor that will impact utilization in this and other applications is the emerging regulations under the Resource Conservation and Recovery Act (RCRA) of 1976. Restarting of this and possibly other projects depends on future RCRA implications [37].

3.2.4.3 TRW [61, 63, 64]

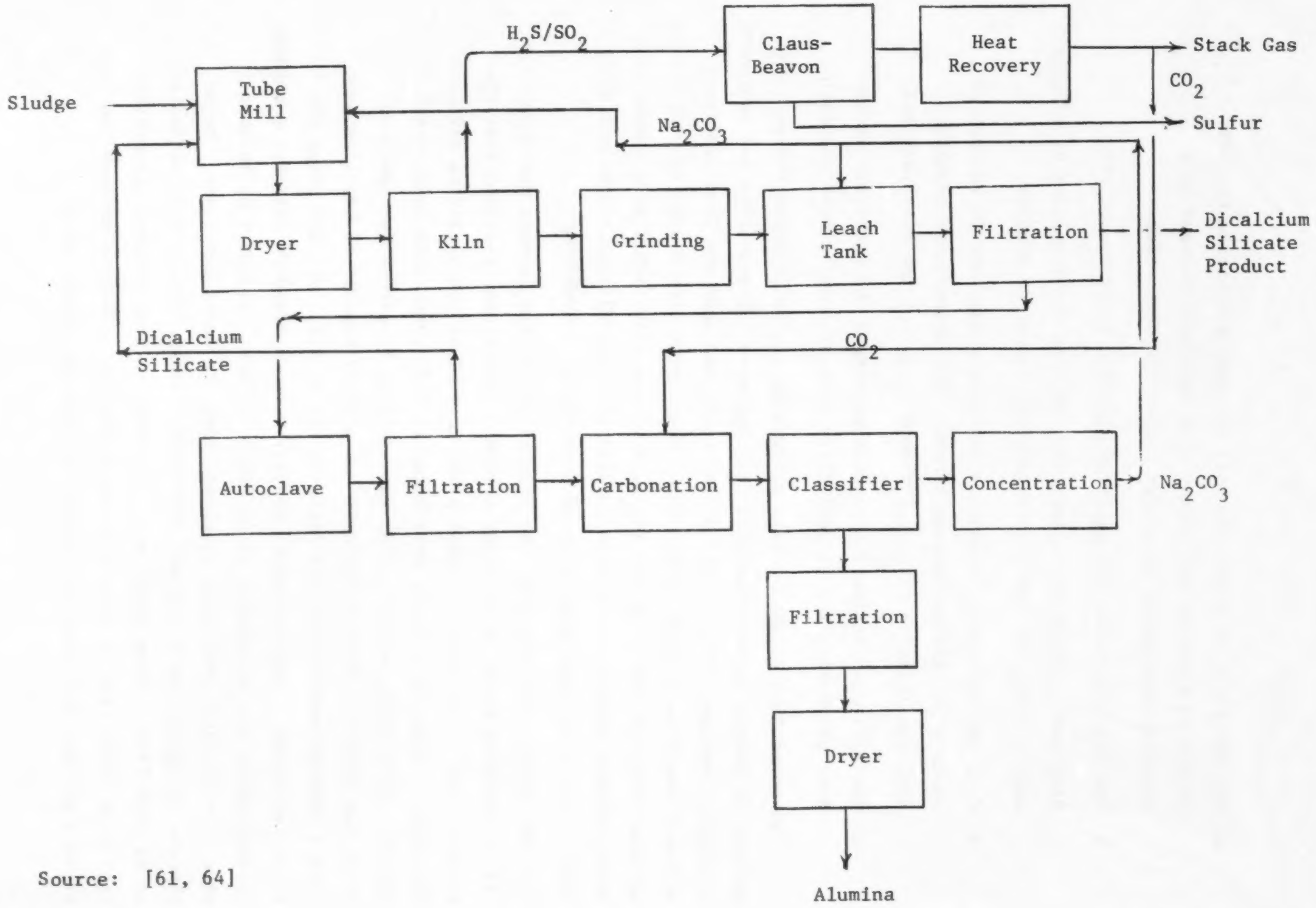
TRW Systems has completed a preliminary process design and economic evaluation of a process to use lime/limestone FGD waste for the extraction of alumina from low-grade kaolin clays. Byproduct dicalcium silicate and elemental sulfur are produced, thereby completely utilizing the waste.

In the conceived process (see Figure 3.2) raw kaolin clay, lime/limestone scrubber waste, sodium carbonate solution, and recycled desilication residue are ground and mixed in tube mills. The mixture is dried, sintered at 780°C (1436°F), and reduced with carbon monoxide (CO) at 1200°C (2192°F) to produce soluble sodium aluminate ($Na_2O \cdot Al_2O_3$) and insoluble dicalcium silicate ($2SiO_2 \cdot 2CaO$) plus hydrogen sulfide gas (H_2S), sulfur dioxide (SO_2), and combustion gases. Most of the H_2S and SO_2 are fed to a conventional Claus unit producing elemental sulfur and a Beavon tailgas plant.

The cooled solids are leached with sodium carbonate (to dissolve the alumina) and filtered to remove the dicalcium silicate; residual dicalcium silicate is precipitated from solution with lime. The alumina trihydrate is precipitated from the pregnant solution by adjusting the pH with combustion offgases (CO_2 carbonation), filtered, washed, dried, and calcined at 1093°C (2000°F) to alumina. The remaining solution is concentrated and recycled. Dicalcium silicate is washed, filtered, and sent to an adjacent cement plant where it substitutes for lime and silica feedstocks.

The process is predicated on several technical assumptions, the validity of which need to be demonstrated before the process could be considered technically feasible. These assumptions include:

- One ton of waste requires 0.012 ton of soda ash, 0.30 ton of clay, and 0.273 ton of coal, and will produce 0.07 ton of alumina 0.156 ton of sulfur, and 0.625 ton of dicalcium silicate.
- The sintering-reduction reactions proceed in the proper sequence and produce a given offgas composition; otherwise, an absorption plant may be needed for the Claus unit.


Sludge
Tube Mill
H₂S/SO₂
Claus-Beavon
Heat Recovery
Stack Gas
CO₂
Sulfur
Na₂CO₃
Dryer
Kiln
Grinding
Leach Tank
Filtration
Dicalcium Silicate Product
Dicalcium Silicate
CO₂
Autoclave
Filtration
Carbonation
Classifier
Concentration
Na₂CO₃
Filtration
Dryer
Alumina

Source: [61, 64]

Figure 3.2 TRW Process Flowsheet

- The reactions of soda, alumina, calcium, and silica to form dicalcium silicate and sodium aluminate will proceed in a reducing atmosphere to a high percentage completion.
- The reaction rates are sufficiently fast to be practical.
- Side reactions do not occur which inhibit the formation of soluble sodium aluminate and thus negate the output of alumina.
- Coal can be used to produce a reducing atmosphere in the proper amounts in this processing scheme. The process may require a coal gasification reactor for some or all of the coal required.
- The dicalcium silicate byproduct possesses the necessary mechanical properties for compatibility with standard cement manufacture.

TRW noted that an alternative processing scheme in which the principal product is cement (tricalcium silicate) may have the potential for increased economic leverage. This latter scheme would use sand and lime/limestone scrubber waste as primary feedstocks. Physically, the design of such a process need not extend beyond grinding of the kiln sinter and, hence, would require significantly less capital than the alumina extraction process. Such a process would also be less energy intensive.

The study concluded that the alumina extraction process was commercially feasible based on existing economic conditions, provided that the process complex includes a cement plant to utilize the dicalcium silicate byproduct. Investment costs were based on 1975 costs (M&S index = 444.3). Interest rate during construction was taken as 9% with a two-year construction period. Total investment for a plant capable of handling waste from a 1000-MW power plant was estimated to be $51.5 million using the Bureau of Mines "study estimate" method; using a standard estimating method, capital costs are calculated to be $52.2 million. Standard techniques were used to ratio purchased equipment costs to installed costs. Major process equipment was sized and estimated. Raw materials were estimated as of July 1976. These costs were used with various assumed discounted cash flow (DCF) rate of return on investment to calculate minimum required alumina prices, both with and without a combined cement plant.

A parametric evaluation of cost sensitivity was done to assess the affect of raw material costs, by-product credits, energy costs, and DCF rate on either alumina price or required sludge credit for a given alumina price. Some of the salient results are presented below. (See Table 3.2.) For comparison, the current market price of alumina is about $140/ton [65]. Note that the bulk of the analysis was done without a combined cement plant, but the results still are generally applicable. A definite economic advantage exists for the combined alumina/cement plant.

The required price for alumina is sensitive to the rate of return, sulfur credit, sludge credit, and coal cost. Depending upon what values are chosen for these variables, the alumina produced may or may not be economically marketable. TRW used a discounted cash flow rate of return of 10-15%. This appears low considering the level of risk inherent in this type of project. A higher rate of return would increase the required alumina prices even more than the values indicated here.

The study recommended that any further work concentrate on (1) verifying the technical assumptions, and (2) considering production of cement as the principal product.

3.2.4.4 Texas A&M University [62]

Northern States Power Corporation (NSPC) is sponsoring a study at Texas A&M which is looking at the feasibility of using FGC waste for the production of lightweight aggregate. NSPC uses aqueous limestone and fly ash for scrubbing and produces FGC waste. Texas A&M has produced lightweight aggregate from this waste in a muffle furnace. Investigations are cu-rently underway on a pilot plant unit which will utilize a rotary kiln. The aggregate is produced by mixing clay and sludge, agglomerating, and firing in the kiln.

This portion of the study is focusing on a technical assessment of the pilot unit. If the process proves technically feasible, market and economic studies will be conducted.

Table 3.2

TRW: Sensitivity Analysis

Case	Combined Cement Plant	Coal Cost	Clay Cost	Capital Cost	Sludge Credit	Cement Credit	Sulfur Credit	Estimated Alumina Cost		
								10% DCF	12% DCF	15% DCF
Sludge Credit $1-$10	No	$20	$6	$52M	$1	-	$10	$370	$404	$461
					$5			$292	$327	$383
					$10			$195	$229	$286
Capital Cost ±50%	No	$20	$6	$52M	$5	-	$10	$292	$327	$383
				x0.5				$193	$210	$237
				x1.5				$392	$444	$529
Clay Cost $1-$10	No	$20	$1	$52M	$5	-	$10	$270	$304	$360
			$6					$292	$327	$383
			$10					$310	$385	$401
Coal Cost @ $40		$40	$6						$468	
Sulfur Credit $0-$25	No	$20	$6	$52M	$5	-	$0	$315	$349	$405
							$10	$292	$327	$383
							$25	$259	$293	$350
With Cement Plant-Sludge Credit $0-$10	Yes	$20	$6	$87M	$0	$50	$10	$221	$279	$369
					$5			$124	$182	$272
					$10			$27	$85	$174

Source: [64]

3.3 Utilization of Wastes and By-products from Recovery FGD Systems

3.3.1 Introduction

As a category, recovery processes differ from nonrecovery processes in that they are designed to produce a high purity by-product sulfur compound with an existing, established market. At present, only systems producing elemental sulfur, concentrated sulfuric acid and/or concentrated SO_2 are considered to be recovery systems in the United States. In a sense, processes producing a high quality gypsum by-product could also be considered recovery systems as they are in Japan; however, in the United States, there are no commercial FGD systems designed for the production of relatively high quality gypsum intended for sale. Most processes now being considered are geared more toward the improvement of system performance (e.g., minimization of scale prevention, improved limestone utilization, etc.) and enhancement of waste properties for disposal operations, rather than manufacturing a product. Present gypsum-producing processes are therefore thought of in the United States as nonrecovery systems, and the utilization of FGD gypsum has been discussed along with other wastes from nonrecovery systems.

Recovery processes (those producing sulfur, sulfuric acid or concentrated SO_2) can offer potential advantages over nonrecovery systems in that they simultaneously produce a by-product chemical where there is an existing market and reduce the volume of FGC wastes that may have to be discarded. However, the total volume of FGC wastes produced will still be high, since coal ash will still be generated and the recovery systems themselves also produce a small amount of waste.

There are a number of factors, however, which may tend to offset the advantages of a saleable by-product and the reduction in waste volume and which may ultimately impact the viability of producing sulfuric acid and/or sulfur in many cases. The most important of these factors are as follows:

- Production of waste streams which require treatment and disposal,

- Immediate and longer-range marketability of by-product sulfur and sulfuric acid,
- Feasibility of stockpiling by-products such as sulfur in anticipation of a future market, and
- Increased energy demands of many recovery systems, especially those producing sulfur.

3.3.2 Waste Streams from Recovery Processes

Recovery processes require separate removal of fly ash. Consequently, fly ash and bottom ash are collected separately and may be maintained as separate products from the by-product of recovery. Therefore, all products are potentially marketable on a segregated basis; this may be an advantage. In addition, since FGD waste essentially is reduced or eliminated, fly ash which might be needed to stabilize waste can now be marketed. In the future, nonrecovery processes may require greater and greater amounts of potentially saleable fly ash to stabilize FGD wastes. Therefore, one potential advantage of recovery processes would be that more fly ash could be utilized in a direct fashion rather than being used to stabilize FGD scrubber waste.

On the other hand, no recovery system is likely to be waste free. All of the commercially available recovery processes as well as those now being demonstrated on a utility scale boiler produce some form of waste in addition to the by-products. The most highly developed recovery systems (Wellman-Lord process, magnesium oxide scrubbing, citrate process, and aqueous carbonate scrubbing) are wet processes and involve contacting the flue gas with absorbent solutions or slurries analogous to nonrecovery systems. These systems cannot tolerate any significant contamination of the absorbent liquors with fly ash, chlorides, or possibly other trace species present in the flue gas. These impurities can interfere with the system chemistry and/or contaminate the by-product. Hence, application of these wet processes to combustion boilers, particularly coal-fired boilers, would normally require incorporation of a prescrubber ahead of the SO_2 absorber, even where a high-efficiency precipitator is used for particulate control.

In addition to removing chlorides, residual fly ash, and some trace species which would otherwise be trapped in the absorber, such prescrubbers also can remove significant quantities of SO_2. The blowdown from these prescrubbers is therefore acidic and can contain appreciable levels of suspended solids as well as potentially higher levels of soluble species than present in many nonrecovery wastes. Treatment of the blowdown prior to discharge can result in waste quantities equivalent to as much as 15% of that produced by nonrecovery systems.

Some of the processes such as the Wellman-Lord process and magnesium oxide scrubbing produce secondary waste streams. In the case of the Wellman-Lord system, it is an impure sodium sulfate waste cake. Sodium sulfate is formed by oxidation of the sulfite absorbent. Since it cannot be readily regenerated to an active alkali, it must be purged from the system. If there is no ready market (e.g., local sodium-based pulp and paper mill) it must be disposed of.

In the case of magnesium oxide scrubbing, magnesium sulfate may need to be purged if oxidation levels exceed steady-state levels consistent with the ability to convert it to magnesium oxide.

3.3.3 Marketability of Sulfur or Sulfuric Acid

A key market-related constraint on recovery FGD systems is the geographic limitation of the market for elemental sulfur and sulfuric acid. Transportation costs limit the marketing radius for sulfur or sulfuric acid. Sulfur or sulfuric acid from recovery FGD systems would have to potentially compete against sulfur from other sources including Frasch sulfur, sulfur from smelters, and sulfur from sour-gas sweetening. In certain specific locations, a local market may exist with these constraints. However, there does not appear to be a sufficient market on the large scale in the immediate future for the sulfur or sulfuric acid that would be produced if a significant percentage of power plants produce by-product sulfur or acid.

Furthermore, markets for these products are currently constrained by oversupply in some areas; and the cost for producing the by-product with FGD systems is high. Therefore, the market potential for these types of utilization products is probably limited, except in special cases. By-products from recovery processes can probably be successfully marketed:

- In specific locations where a market for the products exists because of limited supply from other sources (e.g., transportation constraints), or
- In areas where availability of disposal options for nonrecovery processes is so constrained that the cost of disposal of wastes is higher than the marketing costs for these by-products.

This potential for utilization of nonrecovery processes will be very site-specific.

3.3.4 Stockpiling

Since about 80% of sulfuric acid is produced from elemental sulfur, these chemicals are highly interrelated. Sulfur has a number of other uses including hydrotreating, fertilizer, insecticides and vulcanization; and research activities continue to develop new uses for sulfur (e.g., road construction). While most current demand is met by the Frasch (from the Gulf coast) process, at some future date these sources may be depleted. Further, energy requirements may limit recovery of low-grade Frasch deposits. TVA [56] concludes that over the long-term a greater portion of the sulfur will have to come from other than natural sources. Beyond the year 2000, demand for sulfur is projected to exceed supply [66]. Then alternative sources could be important. In fact, stockpiling might be one alternative for utilities which could not find an immediate market outlet for by-product sulfur. Stockpiling of sulfuric acid is not practical due to technical difficulties. Stockpiling of elemental sulfur however, would be feasible if sufficient incentives existed. Stockpiling could be considered a special type of future utilization. At present, the full implications--technical, financial and institutional--of stockpiling are not known.

3.3.5 Energy Demands

The production of elemental sulfur from recovery processes requires the use of some form of reductant such as natural gas, hydrogen, carbon monoxide or coke. Those processes which produce an intermediate stream of concentrated SO_2 for conversion to sulfur (Wellman-Lord, magnesium oxide) can utilize natural gas directly (the Allied Chemical process) or H_2S (conventional Claus). The citrate process also utilizes H_2S to produce sulfur by reaction with the sulfur-laden absorbent solution. The hydrogen required can be produced by steam reforming a suitable feedstock such as naphtha or possibly by coal gasification. However, coal gasification technology is not as advanced as the recovery systems and adds another level of complexity to FGD systems. Hence, the principal source of reductant for conversion to sulfur, at least for the next few years, would probably be natural gas or naphtha. Aside from the economics, the uncertainties in supply and the potential constraints on natural gas and naphtha consumption could be problematic.

In addition to coal gasification, there are other alternatives now being researched which could avoid the need for natural gas or naphtha. These include: the Foster Wheeler RESOX process in which SO_2 is reduced by passage of the gas through a bed of anthracite coal (a development program is now being sponsored by EPRI in West Germany); and the aqueous carbonate FGD process which utilized petroleum coke or coal for direct reduction of spent scrubbing liquors (a demonstration process is now being funded by EPA). Allied Chemical also has a coal reduction process. However, these processes are many years from commercialization and the current potential shortages of natural gas and oil could impact the implementation of recovery systems.

3.4 FGD Waste and By-product Marketing

Previous work [11, 38] has indicated a variety of potential uses and markets, but the work devoted to definitive market assessment studies or utilization economics has been limited. In part, this has been due to variability in FGC wastes and uncertainties in waste processing and conversion costs. Unknowns regarding waste properties affecting utilization coupled with institutional constraints can also act as dissentives to utilization where FGC wastes would be a substitute for existing materials Examples include the use of FGD gypsum as a substitute for natural gypsum in the manufacture of construction materials (e.g., use in wallboard and cement) and the use of stabilized wastes as fill materials. However, future shortages of chemicals, mineral products and construction materials may alter the incentives for utilization of FGC wastes (both fly ash and FGD wastes).

TVA has recently completed a series of studies for the EPA [37, 56, 67] assessing the potential marketability of wastes and by-products for which conventional markets exist--sulfur, sulfuric acid and gypsum. Generalized cost models were developed comparing a clean fuel strategy with nonrecovery scrubbing, and scrubbing systems producing the desired by-product (gypsum, sulfur, or acid). In all cases, the SO_2 control strategy was selected on the basis of minimum cost for compliance where compliance was based on NSPS regulations for new boilers or the applicable state implementation plan (SIP) for existing boilers as of 1976. Nonrecovery scrubbing was based on the conventional limestone slurry process producing sulfite or sulfate-rich material. Sulfuric acid production utilized the MgO scrubbing process and sulfur production was based on Wellman-Lord/Allied technology. Production of gypsum was assessed for three gypsum-producing FGD systems--limestone-gypsum, Chiyoda Thoroughbred 101 (Japanese technology), and the Dowa process (aluminum sulfate absorption)--and the limestone-gypsum process was chosen for the market cost comparison. The analysis was carried out under the assumption that abatement gypsum would be interchangeable with natural gypsum and the supply price of natural gypsum would be \$3-\$6/ton.

For those plants where production of sulfur, gypsum or acid was the low-cost control strategy, a market simulation model was used to evaluate the distribution of by-products in competition with existing markets. A production cost module was used to predict market costs for elemental sulfur producers, sulfur-burning sulfuric acid producers, by-product sulfuric acid producers (associated with smelters), and gypsum supplied to wallboard plants and cement plants. A linear programming costing model was developed which minimized the total cost to both the acid and the utility industry subject to acid and gypsum demands being met either from traditional sources or from substitution of abatement by-products, given production costs for each sulfuric acid plant, each wallboard plant and cement plant, and the cost of producing and transporting abatement acid, sulfur, or gypsum at each U.S. utility.

The entire U.S. utility industry was characterized from Federal Power Commission data with respect to plant age, fuel type capacity, load factors, and SO_x emission rates for 1978 (projected). Out of a total 3382 boilers at 800 power stations, 833 boilers at 187 stations were projected to be out of compliance and were the subject of this investigation.

In general, the results of the study indicated that taking into account the credit for sales of the by-products, production of sulfur, acid, or gypsum can be competitive with conventional direct limestone scrubbing producing waste for disposal. Gypsum was found to be marketable in isolated instances and sulfuric acid was marketable in areas near utilities but remote from traditional sources of supply; however, sulfur was generally not competitive with other sources of sulfur.

Specific conclusions regarding the marketability of by-product acid and sulfur, and gypsum that were reached are:

> Acid and Sulfur: For the alternatives and technologies considered, acid production was a less costly alternative than sulfur production in all cases. At $60 per ton sulfur, and $.70/MBtu increment for compliance fuel, the amount of acid produced and marketed would be approximately six million tons from 29 plants; an additional five million tons would be available as a low cost alternative but was not competitive with acid produced from sulfur. The amount of substitution is very sensitive to the assumed price of sulfur. Generally, (as could be expected) the by-product acid was competitive in markets supplied by smaller, older, remotely located conventional acid plants.
>
> Gypsum: Table 3.3 summarizes the results of the study regarding gypsum marketability. For the conditions and

Table 3.3

Summary of TVA Gypsum Marketing Results

Total number of plants out of compliance	187
Lowest-cost strategy	
Clean fuel, number of plants	71
Limestone slurry process, number of plants	86
Gypsum production and marketing, number of plants	30
Total gypsum produced, tons	2,400,000
Average production per steam plant, tons	80,000
Smallest gypsum supplier, tons	6,700
Largest gypsum supplier, tons	171,000
Total gypsum sold, tons	2,230,000
Total gypsum stockpiled, tons	171,000
No. of plants where part of production was stockpiled	5
Wallboard plants served	1
Cement plants served	92
Sold to wallboard plants, tons	95,000
Sold to cement plants, tons	2,135,000
Total net revenue to utilities, $	11,076,000
Total savings to gypsum industry, $	1,900,000
Savings to gypsum industry, % of total cost	1.5
Average savings per ton of gypsum purchased, $	0.86
Total first-year compliance cost for 113 plants using the limestone slurry process, $	2,038,000,000
Reduction by marketing gypsum, $	11,076,000
Cost reduction, %	0.5
Required sulfur removal, tons	4,109,000
Sulfur removed by gypsum process, %	8.7
Reduction in sludge disposal by limestone slurry, %	8.0
Imported gypsum displaced, tons	856,000
Domestic gypsum displaced, tons	1,372,000
1978 calcining market served with abatement gypsum, %	0.8
1978 cement market served with abatement gypsum, %	67.0

Source: [67]

alternatives considered, it was found that 15 plants could produce gypsum from flue gas desulfurization at a lower cost than that of conventional direct limestone scrubbing generating waste for disposal. These 15 plants would produce 863,000 tons of gypsum annually. An additional 25 plants could meet compliance using gypsum producing FGD technology at an incremental cost over conventional direct limestone scrubbing of less than $3/ton (the crude gypsum mining cost). These additional 25 plants could produce another 3.4 million tons of gypsum annually.

Of these 40 potential plants, 30 plants could produce and market about 2.4 million tons of gypsum in competition with the natural material. These 30 plants would serve a total of 93 demand points. Only one wallboard plant would purchase abatement gypsum, while 92 cement plants would utilize the remainder (partly because of the higher price offered by cement plants).

The utilization of abatement gypsum at 92 cement plants represents substitution for about 67% of the projected use of natural gypsum in cement production. Of the total gypsum used by cement plants, approximately 1.1 million tons were projected to be imported. Abatement gypsum was estimated to replace about 74% of this imported gypsum.

Use of gypsum-producing technology at the 30 power plants would solve only 8.7% of the electric utility sulfur oxides compliance problem and reduce the required ponding of calcium solids by 8.0%.

In general, production and marketing of abatement gypsum to the cement industry appears to offer an opportunity for steam plants with low annual volumes of sulfur removal to lower their cost of compliance. There appears to be little opportunity to lower compliance cost by marketing abatement gypsum to the existing wallboard products industry. The gypsum production alternative appears to offer only a limited potential to solve the utility compliance problems; however, in terms of a total program of waste utilization, the gypsum production alternative may fill a specific role in that it appears to meet the needs of small plants when other by-products may be better suited to large plants.

Locational considerations were shown to play a major role in determining the feasibility of marketing of abatement gypsum. Specific location studies for each plant where gypsum offered an economic advantage, were recommended. This could also include the feasibility/marketability of new wallboard producing plants.

This study by TVA as well as most all other studies performed to date on the utilization of FGC wastes and by-products are generally based upon conventional uses and existing market structures. A number of factors could impact the future potential for waste and by-product utilization, including:

- Regulatory incentives or disincentives for utilization,
- Changes in institutional constraints,
- Depletion of existing sources of equivalent raw materials or chemicals that can be derived from flue gas desulfurization,
- Development of new, more cost-effective FGD technologies, and
- Development of new uses for wastes and by-product values.

4.0 REGULATORY CONSIDERATIONS

Utilization of FGC wastes is not expected to be significantly encouraged or restrained by recent environmental legislation. Implementation of the Toxic Substances Control Act (TSCA) conceivably could impact new uses; while the Resource Conservation and Recovery Act (RCRA) ultimately could have major impact on utilization. The regulations under these laws are still emerging.

The utility industry is concerned that RCRA, at least in its present form, may not encourage utilization. The National Ash Association has expressed this concern [24]. These organizations are concerned that [24]:

- The emphasis of RCRA may be on disposal, at least over the near-term, and
- The "use constituting disposal" issue may impede utilization.

Over a long term, RCRA is clearly intended to enhance recycle of materials.

The TSCA established within the EPA the Office of Toxic Substances (OTS), with broad authority to regulate the entry of chemicals into the environment. With an estimated 43,000 chemicals already in commerce, and new ones coming into use at a rate of about 1,000 per year [68], it will be necessary for the OTS to set priorities for determining which chemicals to test and regulate. Because many of these thousands of chemicals are known to be far more important in terms of toxicity than FGC wastes, it is anticipated that the OTS will not regulate utilization of these wastes. The necessity of prioritizing chemicals for testing was recognized in the Act in Section 4(e), which established the Interagency Toxic Substances Testing Committee which advises the EPA of priority chemicals for testing. To date, the committee has listed 21 chemicals--FGC wastes are not listed. Unless important toxic effects from FGC waste utilization are observed, it is highly unlikely that the OTS will regulate them in the next 5-10 years.

The OTS has concentrated on two sections of the law to date, those calling for an inventory of chemicals already in production and use, and the development of procedures for premanufacturing notification by industry of its intent to market a new chemical.

The publication of the inventory has been delayed by over a year from its mandated deadline [68]. The questionnaire was distributed to electric utilities, and FGC wastes were reported as existing chemicals already in use. This would exempt them from the premanufacturing notification requirements in the future, unless they were being marketed for a significant new use.

Procedures for premanufacturing notification have not yet been established; these rules were only proposed in January 1979. They are unlikely to significantly restrain utilization and hence will not be discussed further here.

The objectives of the RCRA include (Section 1003) the conservation of valuable material by:

- Providing technical and financial assistance to the states and local government bodies which will promote new and improved methods of recovery of solid waste,
- Providing for establishment of guidelines for the recovery of solid wastes,
- Promoting research and development for recovery and recycling of solid wastes,
- Promoting the demonstration, construction, and application of resource recovery systems, and
- Establishing a cooperative effort among federal, state, and local governments and private enterprise in order to recover valuable materials from solid wastes.

Based on these objectives the Act would be expected to encourage the utilization of FGC wastes. However, there are few substantive provisions of the Act which will encourage use of FGC wastes. The strength of the Act is in the solid waste and hazardous waste management plans, which provide for the environmentally sound disposal of wastes.

Section 2003 provides for the establishment of "Resource Conservation & Recovery Panels" - teams of personnel to provide technical assistance to states and local governments on solid waste management, resource recovery, and conservation. Funding for this program is $7-8 million per year.

State solid waste management plans established in Subtitle D are prohibited from hindering resource recovery, but only limited incentives for resource recovery are provided at present.

In Subtitle E, the Department of Commerce "shall encourage commercialization of proven resource recovery technology by providing:

(1) Accurate specifications for recovered materials, and
(2) Stimulation of development of markets for recovered materials. . ."

The specifications pertain to chemical and physical properties of such materials with regard to their viability in replacing virgin materials in various uses.

In Subtitle F, federal agencies are required to use recycled materials to the greatest extent practicable. Government specifications for procurement of materials must not exclude recovered material. EPA is responsible for setting guidelines for federal procurement of recovered materials. Section 6002(e) of RCRA focuses on the setting of guidelines for the federal procurement of recovered materials. Ultimately, this could have a significant impact on the extent of utilization of FGC wastes. Finally, Subtitle H provides funding for research into resource recovery.

In addition, another significant support for FGC waste utilization is the requirement that the Department of Commerce provide adequate specifications for recovered materials pertaining to their use in replacing virgin materials.

5.0 ASSESSMENT OF UTILIZATION AND DATA GAPS

5.1 Assessment of Utilization

In 1977 total U.S. production of coal ash (fly ash, bottom ash, and boiler slag) was 61.6 million tons with 12.7 million tons successfully recovered and utilized [3]. This is more than three times that used by any other nation during the same time period. On a percentage basis, 21% of the ash produced was thus utilized. In contrast, Western Europe uses a much higher percentage of their coal ash and Japan uses a much greater percentage of their production of FGD wastes. A variety of explanations have been given for this fact, usually in some way related to the research perspective of the organization doing the assessment. Specifications, quality control, lack of markets, consumer bias, lack of technical development, and many other reasons have been put forward and are hindering increased utilization of ash and sludge in the United States. All of these reasons are valid in at least some instances, and some are universally valid. On balance, a combination of three types of factors constrain FGC waste utilization:

- Technical considerations, particularly in comparison with alternative materials,
- Institutional barriers related to poor understanding of the by-products and failure to develop markets by either the utility industry or user industries, and
- Possible environmental concerns related to some uses.

5.1.1 Technical Considerations

Since coal ash and FGD wastes are by-products, quality control in the production of these materials is a major factor. Utilities are in the business of producing power; ash and FGD wastes are simply by-products of their operation. Since ash and FGD waste characteristics are influenced by coal properties, system design, and operating conditions, quality control at the utility can be a problem. Some progress has been made in setting appropriate standards for quality in FGC wastes for utilization purposes. In some instances, uncertainty exists as to what waste properties are important for a particular use. Additional standards and acceptance by users are needed to make utilization more attractive.

Transportation of the FGC wastes is another constraint. Since most proposed uses are in low value applications, the economic radius of the market is often small. Virgin materials may also have a more desirable transportation rate structure. The economic margin in favor of FGC waste use in preference to an alternative material is usually not large.

5.1.2 Institutional Barriers

Perhaps the largest institutional barrier has been that the potential consumer industries for FGC waste utilization are conservative, traditional industries. Such an industrial sector is reluctant to consider new approaches that would be required if FGC wastes are to be used. Furthermore, from the utility viewpoint, it is preferable to have all FGC wastes handled through a single source as opposed to many small consumers buying from them. Since most users cannot accommodate the entire output of a large utility, brokers can enter the picture (as well as for other reasons) which adds another variable. Tax and transportation rate structures also disfavor by-product use. Basic changes would have to occur in all of the above factors if FGC by-product utilization is to be encouraged.

5.1.3 Other Factors

A variety of less obvious issues also plague utilization. The potential effect of RCRA regulation is of concern vis-à-vis disposal. There also is concern over whether fly ash could be declared toxic or radioactive. Product liability concerns may have an effect on utilization. The high rate of inflation and the rapid rise in energy and raw material costs make the task of assessing the economic viability of new utilization schemes in the future somewhat arbitrary. An issue requiring clarification to enhance FGC waste utilization is that related to short and long-term liability. There is some hesitancy on the part of some sectors of the industry to sell FGC wastes for use in otherproducts such as wallboard or cement. If at a future date a product made with FGC wastes as one of the raw materials is found hazardous or harmful, what will be the liability to the generator of FGC wastes? All of these concerns, as well as others, both by themselves and in combination tend to hinder increased utilization of FGC wastes.

Considering the anticipated growth in the generation of FGC wastes, removal of, or reduction in, barriers to FGC waste utilization becomes important. In some cases, technical problems preclude successful large-scale utilization. The more serious impediments are apparently institutional in nature but can potentially be overcome by concerted efforts. Utility companies previously have been concerned primarily with the production of electricity: marketing of waste by-products has been secondary. Wastes have been viewed as a nuisance and liability rather than as a potential asset to be sold and produced along with electricity. The utility companies not only need to envision the importance of marketing their FGC wastes as by-products, but also must aggressively develop markets with education being a key factor in overcoming the reluctance on the part of many industries to utilize FGC wastes. Potential users are concerned about chemical and physical variability of the material, lack of existing specifications for use in manufacturing processes, and fear of a lack of constant supply depending upon the vagaries of plant operation. Furthermore, in those uses where environmental or other regulatory concerns exist, policy decisions are needed to remove elements of uncertainty.

5.2 R&D Assessment

The use of fly ash in construction (e.g., cement, concrete, aggregate, fill) is a relatively highly developed end-use. These materials are in widespread full-scale commercial use on a routine basis. Little research is currently being done on new end-uses within the construction sector because of this development. However, several organizations either have been or currently are sponsoring a variety of technical programs aimed at identifying and quantifying the effect of fly ash on these materials. Much of this work is aimed at concrete (NBS, Bureau of Reclamation, Corps of Engineers) although work has been done by the FHWA on use in road construction. It appears that any additional EPA research activity in technical areas beyond what is currently ongoing is not warranted.

Stabilization of FGD waste represents a significant potential for using fly ash. However, this is probably more appropriately considered a disposal option. Any additional research sponsored by the EPA on the utilization aspects of this end-use is probably not warranted.

A variety of new uses for fly ash currently are being investigated, mostly at the research or bench scale level. Some of these processes may prove viable in a longer time frame; some (e.g., vanadium recovery) are currently being practiced on a small scale. It is desirable that this type of research continue, but additional funding by the EPA is probably not warranted at present.

The use of bottom ash and boiler slag is quite extensive, about 60% of the boiler slag is consumed. The markets served are fairly well developed, and use has been relatively constant over the past several years. Additional research is probably not required in this area.

FGD wastes currently are being utilized abroad (notably in Japan) where they are generally oxidized to produce gypsum for sale to the cement or wallboard industry. There currently is no utilization of FGD wastes in the United States, principally because FGD wastes have not been produced in significant quantities until recently (i.e., full-scale lime/limestone scrubbing is relatively new in the United States). The potential utilization of FGD wastes is dependent upon successful solutions of a variety of technical and non-technical problems in addition to those mentioned earlier.

Gypsum production is the only utilization option which is near full-scale commercial development in the United States. The EPA is sponsoring a number of programs which will demonstrate oxidation of FGD waste to gypsum, but these have been aimed primarily at enhancing the disposal properties of the waste. (See Volume 5.) If gypsum production does become a commercial reality, some market penetration can be expected. However, this will still be only a small fraction of total FGD waste generation, estimated to be about 38 to 57 million tons per year by 2000 [1]. The TVA has done some work on the potential market size for abatement gypsum using a least-cost LP model. A continuation of this work on a more general market-institutional level may be useful.

Several other end-uses are being considered by various organizations, but are not at the same level of development as gypsum. TRW has proposed a process whereby FGD waste is used as a reagent for the extraction of alumina from kaolin clay and by-product dicalcium silicate is produced. A sulfur byproduct is produced. Based on the economic analysis, it is unclear whether the process is viable at present.

Two projects are being sponsored by EPA on the development of a sulfur production process, and a fertilizer production process by Pullman-Kellogg and the TVA, respectively. The economics of both processes are uncertain at this time and should be investigated further.

5.3 Future Utilization Considerations and Data Gaps

By the year 2000, the U.S. minerals deficit will exceed the energy deficit, possibly approaching \$100 billion dollars [28]. The United States is currently dependent on foreign sources for 22 of the 74 non-energy essential minerals. Of the 12 crucial elements, seven are imported in quantities greater than 50% of consumption [28, 53]. Utilization of FGC wastes can potentially help offset this deficit and provide an alternative domestic source for a variety of minerals, thereby reducing dependence on imports. The presence of these minerals in coal ash and FGD waste, and the large amounts of FGC wastes available, are incentives for basic R&D on conversion and/or extraction processes.

Much research has already been done on extracting alumina, magnetite, and other minerals from ash and FGD. However, these processes are not currently capable of competing generally with more established processes, and in some cases the market does not exist because of more readily available alternate sources of minerals. However, utilization R&D is really just one facet of a long-term product development program with FGC as the raw material. As such, commercial marketability should be thought of in a long-term (e.g., 10 years or more) time frame and FGC wastes should be considered an eventual source of minerals or other raw materials. This is not to say that some processes might not be viable sooner; only that R&D should not be discontinued because a process does not appear to be economic in the near term.

Additionally, depending upon the current market situation, the abolishment of disincentives or the establishment of incentives may be necessary at the state or national level for the effective promotion of the use of FGC waste as a resource. Ultimately, utilization of FGC waste should be viewed as an alternative source of minerals, not a disposal option, although the promotion of utilization may help to alleviate disposal problems.

An overall product development program may be thought of as a series of steps (see Figure 5.1) which lead to introduction and (hopefully) acceptance of the product in the marketplace. The steps generally follow three distinct lines representing the following criteria:

- Technical feasibility,
- Economic attractiveness, and
- Marketability.

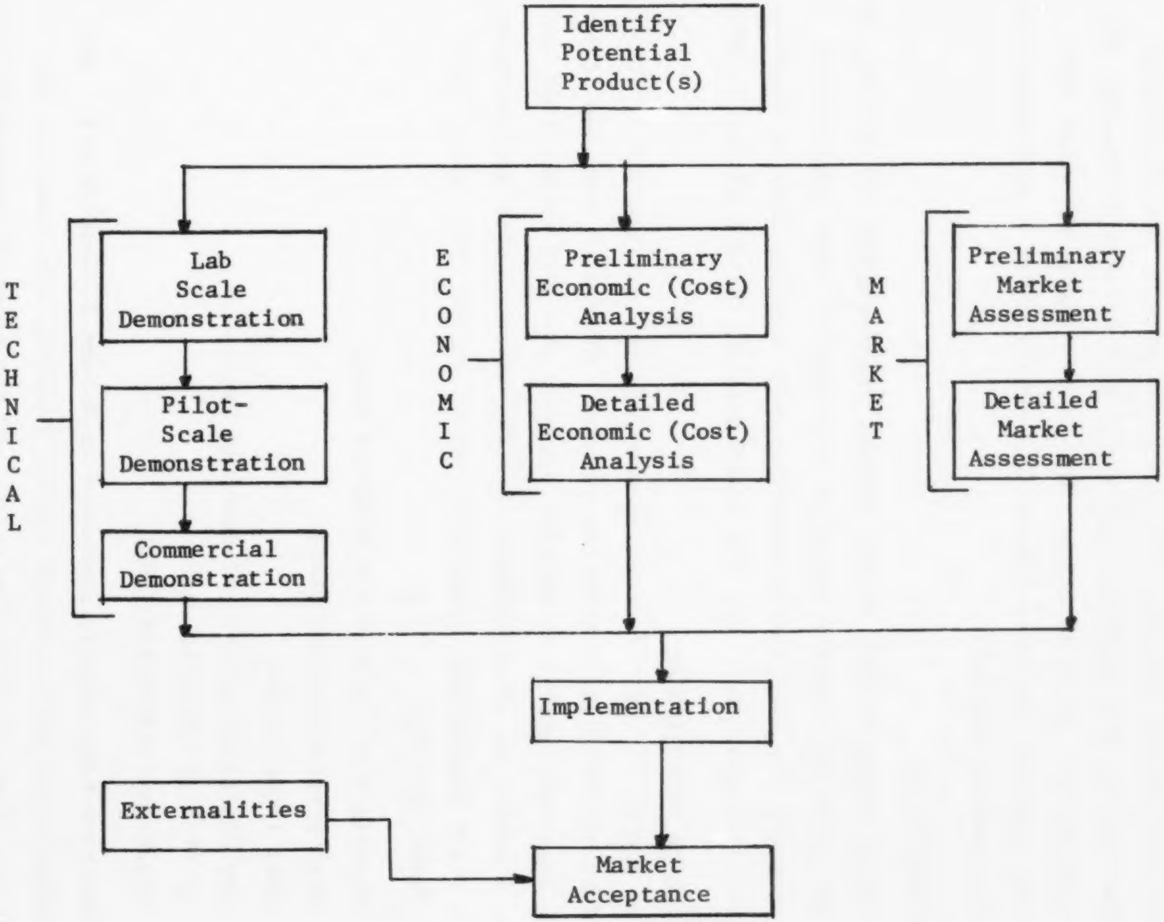
The initial step of identifying the potential products may be quite involved as it ideally looks at all possible products, and considers such things as technical complexity, commercialization requirements, etc., in an evaluation of which products have the greatest probability of success in the largest market. For each product chosen, a technical, economic and market evaluation must be conducted. If all three yield positive results, commercialization (implementation) may begin.

Even if the product is technically, economically and marketably qualified, it may not be accepted in the marketplace for a variety of reasons beyond the direct control of the market (externalities). It is desirable to identify all external influences which may affect market acceptance of the product at the earliest possible date, and to either correct them or adjust for them in the product.

Three areas could benefit from additional research.

Product Evaluation

From a general point of view, which of many products suggested for FGC wastes are the most attractive technically, economically, and in the marketplace, in a 10-20 year time frame?


Identify Potential Product(s)
TECHNICAL
Lab Scale Demonstration
Pilot-Scale Demonstration
Commercial Demonstration
ECONOMIC
Preliminary Economic (Cost) Analysis
Detailed Economic (Cost) Analysis
MARKET
Preliminary Market Assessment
Detailed Market Assessment
Implementation
Externalities
Market Acceptance

Source: Arthur D. Little, Inc.

Figure 5.1 Product Development Logic

Commercialization Requirements

The issue of quality control is a technical area which is still cloudy. From the production point of view, the utility has some control over the carbon content of fly ash, and the characteristics of FGD waste. Which characteristics are important for utilization? How do various properties affect, for example, concrete? What effects do storage and transportation have on utilization? How do ash characteristics vary across the country? How does this affect utilization? Can blending be useful for quality control?

Externalities

A better understanding of the various institutional constraints which affect FGC waste utilization would be very useful. What constraints exist? How are the constraints interrelated? How can they be overcome? Which should be overcome? How are institutional factors different abroad?

5.4 Emerging Technologies

This report has been focused on analysis and utilization of FGC wastes produced by conventional combustion of coal. This will continue to be the most important method to utilize coal for the next twenty (20) years. However, a number of other methods of utilization of coal are emerging and will reach significant commercialization in the next twenty (20) years. These include:

- Fluidized bed combustion (FBC) of coal,
- Coal preparation processes,
- Coal liquefaction,
- Low Btu gasification and combined cycle generation of power, and
- Magnetohydrodynamics (MHD).

These have been largely discussed in Volume 1, Section 4.8. All these technologies will generate wastes; however, the quantity, the physical and chemical characteristics, and the point of generation (mine end, utility end or other) of the wastes would be different from those associated with conventional coal combustion.

Additional focus on the waste generated by such technologies and exploration of potential utilization of such wastes should be an essential part of the development of these emerging technologies.

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